NAVAL ELECTRICIANS' TEXT BOOK

Volume I

THEORETICAL

— BULLARD

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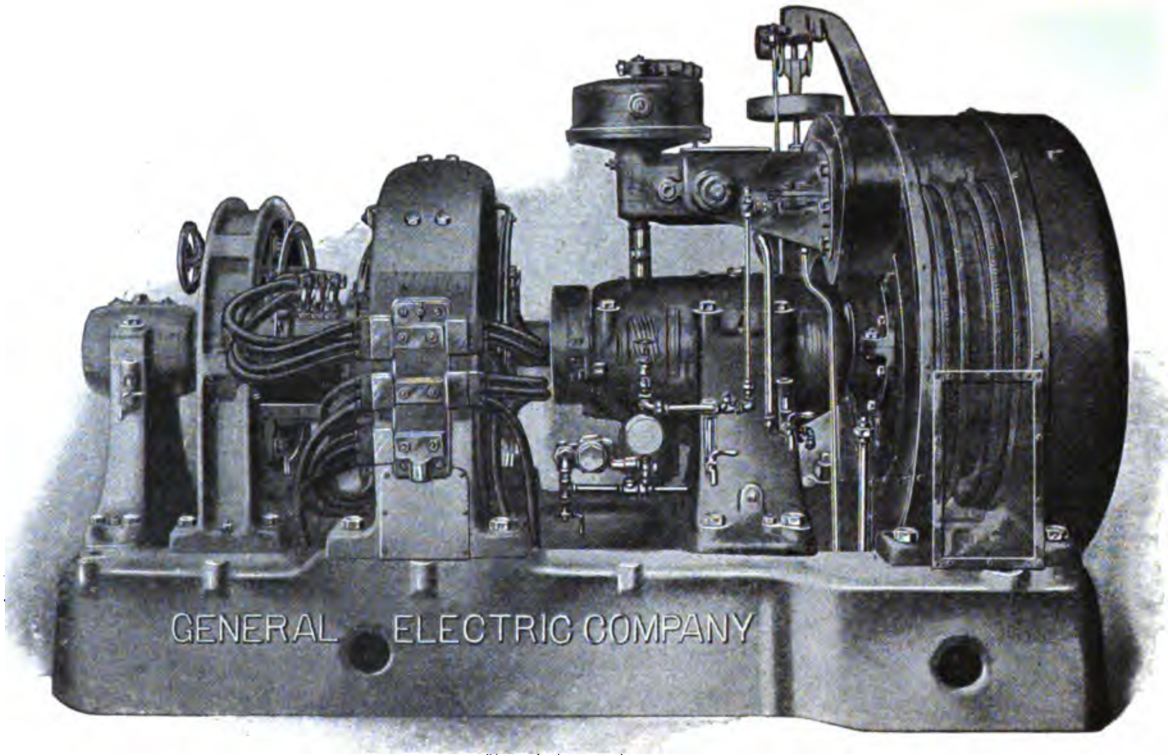

PHANTOM VIEW OF CURTIS STEAM TURBINE DIRECT CONNECTED TO 100 KW. DIRECT CURRENT GENERATOR.

NAVAL ELECTRICIANS' TEXT BOOK

VOLUME I

THEORETICAL

BY

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PREFACE

This book is a revised and enlarged edition of the Naval Electricians' Text and Hand Book. Many new chapters have been added to the original manuscript and all have been more or less rewritten and to such an extent that it has lost its hand-book characteristics. As stated in the first edition, there is probably little or nothing contained in it that cannot be found elsewhere, but an attempt has been made to collect complete information concerning the principles and uses of electricity as applied to our ships of war.

It is primarily intended for use as a text book by midshipmen at the Naval Academy, but officers and the enlisted personnel and electricians should find it a fairly complete treatise on electricity as far as it relates to the subject of our warship installation.

It would be difficult to give credit to all those who have made suggestions foı improvement of the book, but special mention should be made of the officials of the General Electric Company who have contributed many illustrations of the appliances made by them and furnished much valuable manuscript. Due credit has been given to other manufacturers and to those who have allowed the results of their experiments to be used.

W. H. G. Bullard,

Lieut.-Commander U. S. Navy.

PREFACE TO SECOND EDITION

The first edition of the Naval Electricians' Text Book was published in one volume. In an endeavor to bring the subject matter up to date and to keep pace with the constantly increasing installation of electrical material and apparatus in our ships of war, as well as to make it a complete text book covering all electrical principles concerned, the manuscript has grown beyond the proper proportions for a single volume. The present edition has accordingly been made up in two volumes, in one of which the purely theoretical matter has been placed, and in the other, descriptive matter of material, apparatus, methods of control, etc. The division is somewhat arbitrary, but the aim has been to keep the theoretical matter separated from the practical as far as possible.

Much new matter has been added, and while it is impossible to furnish descriptions of every piece of electrical apparatus that is installed on our ships of war, enough typical equipments have been described to illustrate the general subject and to show the electrical principles involved.

The compiler wishes to take this opportunity to express his appreciation of suggestions by many officers of the service, and particularly the assistants in the Department of Electrical Engineering, leading to changes and improvement in the manuscript, and of the courtesies extended to him by manufacturers of electrical apparatus, particularly the officials of the General Electric Company, the Cutler Hammer Electric Manufacturing Company, the Diehl Electric Manufacturing Company, the Walker Electric Company, the Holtzer Cabot Electric Company, the Cutter Electrical Company, the Sangamo Electric Company, the Reliance Electric Engineering Company and Chas. Cory & Son, all of whom have freely furnished much valuable information and data.

W. H. G. Bullard,

Commander U. S. Navy.

July 1, 1911.

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CHAPTER I.

DERIVATION AND DEFINITION OF UNITS.

All units used in the science of electricity are based on the units of the metric system, a system in which certain standards are adopted for measuring the three fundamental quantities of **length, mass** and **time.**

Standards of the Metric System.

Length.—The unit of length in the metric system is a **metre,** and was originally intended to be the one ten-millionth part of the distance from the earth's equator to the pole measured over the surface of the earth along the meridian passing through Paris. The present standard of length is the metre, and is the distance at 0° C. between the ends of a platinum rod preserved in the Archives of the French Capital. This distance is slightly less than the original measured distance, as the earth's quadrant is now found to measure 10,000,880 metres.

Each metre is equal to 10 decimetres, or
100 centimetres, or
1000 millimetres,
and 1000 metres make a kilometre.

A metre is 39.37043 inches, or 3.28 feet.

A decimetre is very nearly 4 inches (3.937 inches).

A millimetre is very nearly equal to $\frac{1}{25}$ of an inch.

The kilometre is about $\frac{5}{8}$ of a mile, or 1093.6 yards.

Mass.—The unit of mass is the kilogramme, and is equal to the weight of the standard kilogramme, a piece of platinum preserved with the standard metre in the Archives at Paris. It is intended to have the same weight as a cubic decimetre of water at its temperature of maximum density, 3.9° C.

The kilogramme is about 2.2 pounds.

Time.—The unit of time is the **second**, and is the $\frac{1}{86400}$th part of a mean solar day.

C. G. S. (Centimetre, Gramme, Second) System.

In the C. G. S. system, the **centimetre**, $\frac{1}{100}$th part of a metre is taken as the unit of length; the **gramme**, $\frac{1}{1000}$th part of a kilogramme is taken as the unit of mass and the **second** is taken as the unit of time.

Derived Mechanical Units of the C. G. S. System.—There are certain mechanical units derived from the three fundamental units, such as *area, volume, velocity, acceleration, force, work, power,* and *heat.* Mechanical and electrical quantities are closely related, and in order that the definitions of the electrical units may be understood, it is first necessary to consider the mechanical units.

Area.—The unit of area is the square of the unit of length, or *square centimetre.*

Volume.—The unit of volume is the cube of the unit of length, or *cubic centimetre.*

Velocity.—The unit of velocity is the velocity of a body that moves through unit length in unit time, or it is a velocity of *one centimetre per second.* It is called the **kine.**

Acceleration.—The unit of acceleration is the acceleration which gives unit velocity in unit time, or an acceleration of *one centimetre per second in one second.* It is called the **spoud.**

Acceleration is the rate of change of velocity. If at a certain instant a moving body has a velocity V, and at the end of a given interval T, it has a velocity V', its change of velocity has been $V' - V$, and the acceleration or rate of change of velocity is

$$A = \frac{V' - V}{T}.$$

One of the most common examples of acceleration is that due to the attraction of the earth, and bodies falling freely under the action of gravity have an acceleration of 32.2 feet per second. This means that at the end of each second, its velocity is 32.2 feet per second greater than the velocity at the beginning of the second.

A body falling from rest will fall 16.1 feet in the first second, as its acceleration is 32.2 feet, which is its velocity at the end of the second, since $V = AT$ and $T = 1$. The average velocity then is

$$V = \frac{0 + 32.2}{2} = 16.1 \text{ feet,}$$

and the distance fallen is the time multiplied by the average velocity, or

$$L = VT = 16.1 \times 1 = 16.1 \text{ feet.}$$

At the end of the second second, its velocity has been increased by 32.2 feet, or it is now $32.2 + 32.2 = 64.4$ feet, and the average velocity in the second second is

$$V = \frac{32.2 + 64.4}{2} = 48.3 \text{ feet,}$$

and the distance fallen in the second second is

$$L = VT = 48.3 \text{ feet.}$$

At the end of the third second, its velocity has been increased by 32.2 feet, or it is now $64.4 + 32.2 = 96.6$ feet, and the average velocity in the third second is

$$V = \frac{64.4 + 96.6}{2} = 80.5 \text{ feet,}$$

and the distance fallen in the third second is

$$L = VT = 80.5, \text{ etc.}$$

The total distance fallen in three seconds is

$$16.1 + 48.3 + 80.5 = 144.9 \text{ feet.}$$

This is also derived as follows:

$$V' - V = AT \text{ and } L = \left(\frac{V' + V}{2}\right) T,$$

or

$$L = VT + \tfrac{1}{2} AT^2$$

in starting from rest $V = 0$, or

$$L = \tfrac{1}{2} AT^2,$$

and in the case above

$$L = \tfrac{1}{2} \times 32.2 \times 3^2 = 144.9 \text{ feet.}$$

Examples of Acceleration.

1. A body travels at the rate of 12 feet per second; in 10 seconds it is moving at the rate of 7 seconds per second; what is the mean acceleration? *Ans.* ½ ft. per sec.

2. A body moves in the first second through a space of 16 feet and in the fourth second through 112 feet, what is the acceleration per second? and how far does it move in the second second and the third second?
Ans. 32 feet per sec.
48 feet 2d sec.
80 feet 3d sec.

Force.—The unit of force is that force which acting for one second on a free gramme mass, will impart to it a velocity of one centimetre per second. The unit of force is called the **dyne.**

Force is an attribute of matter that produces or tends to produce motion or change of motion. Whenever force moves a mass, it imparts to it a certain velocity, and if it moves a unit mass with a velocity of one centimetre per second in one second it will produce unit acceleration and force and mass are thus connected by the formula

$$F = MA$$

the fundamental equation of force.

There are many kinds of force, such as mechanical, physical, electrical, gravitational, etc. It has already been shown how the earth's attraction, or force of gravity, acts to produce acceleration, and the force with which any body is held to the earth is the product of its mass and the acceleration due to the force of gravity. Thus a kilogramme mass is attracted to the earth with a force of

$$1000 \times 981 = 981{,}000 \text{ dynes.}$$

The acceleration of gravity is 32.2 feet per second, or since $1 \text{ foot} = \frac{100}{3.28}$ centimetres, it is

$$\frac{32.2 \times 100}{3.28} = 981 \text{ centimetres per second;}$$

and since $F = MA$, the force on one gramme is

$$F = 1 \times 981 = 981 \text{ dynes.}$$

The unit of force in the English system of units is defined to be that force that, if applied to a pound mass for one second, produces a velocity of one foot per second. It is called the **poundal.**

The force exerted by gravity produces a velocity of 32.2 feet per second, and therefore the force exerted on one pound by the force of gravity is

$$F = MA = 1 \times 32.2 = 32.2 \text{ poundals.}$$

Mass is the quantity of matter in a body and **weight** is a measure of the attraction of gravity on the body; thus the weight of one gramme is

$$F = MA = 1 \times 981 = 981 \text{ dynes.}$$

Examples of Force.

1. A constant force acting upon a mass of 30 grammes causes it to move through 10 metres in 3 secs. starting from rest. What is the value of the force in dynes? *Ans.* 6,666⅔ dynes.

2. Express the weight of 10 kilos. in dynes, and the value of a dyne in terms of a grammes weight. $g = 981$ dynes. *Ans.* 9,810,000 dynes.

$\frac{1}{981}$ grm.

3. A spring balance is carried in a balloon which is ascending vertically. What is the acceleration of the balloon when an 8-oz. weight hung upon the spring balance is found to indicate 9 oz.? $g = 32$. *Ans.* 4 ft. per sec.

4. A body of mass 4 pounds is moving at the rate of 8 feet per second. At this instant a constant force begins to act upon it in the direction of its motion, and after 20 seconds, its velocity has increased to 24 feet per second. Determine the magnitude of the force. *Ans.* 3.2 poundals.

Work.—The unit of work is the work done in overcoming unit force in unit distance, or the work done in overcoming one dyne in one centimetre, or the work done by one dyne working through one centimetre. It is called the **erg.**

Work is done on a body when a force causes it to move or to change its direction of motion. A body does work when it overcomes another force in a certain distance. Thus a locomotive drawing a train of cars does work against the friction of the rails,

resistance of the air, etc. If the force producing the work is removed, if steam is cut off, the train will be brought to rest in a certain distance by the force due to the resistances that were previously overcome. It is necessary to produce motion in some direction for work to be done, however great a force may be applied. A locomotive may exert considerable force but unless the train or itself is moved, it does no work.

The English absolute unit of work is the foot-poundal, and is the work done by a force of one poundal acting through a distance of one foot.

The practical unit is the foot-pound, which is the work done in raising one pound one foot against gravity. Since $F = MA$, the force overcome in raising one pound is $F = 1 \times 32.2$ poundals, and the work done is

$$W = FL = 32.2 \times 1 = 32.2 \text{ foot-poundals.}$$

Therefore, one foot-pound = 32.2 foot-poundals.

Energy.—Energy is the power of doing work. A body may have the power to do work, but yet restrained from doing it. Thus a body held at a given distance from the earth's surface has the power of doing work and can do so if the restraining force holding it is removed. It may fall and do work, as in the case of the hammer of a pile-driver. This energy due to its position is called **potential energy.**

The measure of its potential energy is the amount of work expended in putting it in position. Thus, to raise a certain mass M to a certain height L, requires work equal to

$$W = FL, \text{ but } F = MA$$

and

$$W = MAL, \text{ or } PE = MAL,$$

or the body has potential energy equal to MAL.

If the body falls, the potential energy is converted into energy in motion, or **kinetic energy**, and when it reaches the ground from which it was removed, the kinetic energy will be just equal to its potential energy at its highest point and will be again equal to the work required to raise it.

At the moment of striking the ground, it has a velocity V and its kinetic energy at that instant is

$$KE = \tfrac{1}{2}MV^2, \text{ derived as follows:}$$

It has been shown that

$$L = \tfrac{1}{2}AT^2 \text{ and } V = AT.$$

Therefore,

$$PE = MAL = M \times \frac{V}{T} \times \tfrac{1}{2}\frac{VT^2}{T} = \tfrac{1}{2}MV^2;$$

and since the potential energy at its highest point is equal to its kinetic energy at its lowest,

$$KE = \tfrac{1}{2}MV^2.$$

Examples of Work and Energy.

1. A body of mass, 3 lbs. is projected vertically upwards with a velocity of 640 feet per second; how much work has been done against gravity when it has ascended to half its maximum height?

***Ans.* 9600 ft.-lbs.**

2. An engine is running at the rate of 80 feet per second on level ground, when steam is shut off. Assuming that the frictional resistances are equivalent to a weight of 14 lbs. per ton, how far will the engine run and for how long?

***Ans.* 16,000 feet.**
400 secs.

3. A 4-oz. bullet is projected vertically upwards with a velocity of 800 feet per second. What is its potential energy when it has reached its maximum height?

***Ans.* 2500 ft.-lbs.**

4. A hammer moving at the rate of 12 feet per second hits a nail and drives one inch of its length into a board. The mass of the hammer is half a pound. Assuming it to be inelastic, and to come to rest; find the average resistance it encountered.

***Ans.* 432 poundals.**

Power.—The unit of power is the *erg per second,* and is the rate of doing work. It is connected with the unit of work by the element of time. Two forces may do the same amount of work in different times, and the one that does it in the shorter time is said to be the more powerful, that is, it can do more work in a given interval of time than the less powerful. If an electric motor can turn a turret once completely around in 10 minutes, and another

motor can turn the same turret once in five minutes, the second one does twice as much work in the same interval of time as the first, and it has therefore twice the power of the first one, though they each do the same amount of actual work; they have overcome the same force in the same distance.

The unit of power in the C. G. S. system has no distinctive name, being called the *unit of activity,* or the erg per second.

The practical unit of power in the English system is the horse-power, equal to work done at the rate of 33,000 foot-pounds per minute, or 550 foot-pounds per second.

The practical unit of power in the C. G. S. system is the **watt,** equal to 44.2 foot-pounds per minute.

Examples of Power.

1. Find the horse power, H. P., of an engine which will in 9 hours empty a vertical shaft of water, whose section is 9 sq. ft. and depth 400 feet. Density of water = 62.5 lbs. per cubic foot. *Ans.* 2.525 H. P.

**2. An engine takes a train of 60 tons in all up an incline of 1 in 100 at a maximum speed of 30 miles per hour and it can take a train of 150 tons on the level at the same speed. Find the frictional resistances of the road in lbs. per ton and the rate in H. P. at which the engine works at this speed. *Ans.* 14.193 lbs. per ton.
179.16 H. P.**

Heat.—The unit of heat is the amount of heat required to raise the temperature of one gramme of water from 0° to 1° C. It is called the **calorie.**

The work equivalent to one calorie is equal to 42,000,000 ergs.

The British unit of heat is the amount of heat necessary to raise the temperature of one pound of water 1° F.

The relation of these units is given under the unit of electrical work, the joule.

Units in the C. G. S. and Practical Systems.

The underlying principle of these systems of units is the reaction of a magnetic field upon a unit magnetic pole.

A **unit magnetic pole** is one of such strength that it will repel a similar pole with a force of dyne when separated from it one centimetre in air.

A **unit magnetic field** is one of such strength that a unit magnetic pole placed in it is acted on with a force of one dyne. It is called unit intensity or a **gauss.**

The reaction of a magnetic field upon a unit pole only involves the terms of force and distance, both of which can be accurately measured.

Unit of Current.

An electric current is not a tangible material substance; it cannot be seen; a conductor carrying a current looks to be in the same condition as one in which no current is flowing. It has certain properties; viz., resistance, inductance, and capacity. These depend upon the material, form, and dimensions of the conductors directing the current and upon their relative positions to each other. These properties only become manifest when the circuit is subjected to certain conditions. It will be shown later that electrical resistance is only evident when current is flowing; inductance when current is changing, and capacity when electromotive force is changing.

C. G. S. Unit of Current.—An electric current can only be detected by the effects produced by it. It may produce sound, light or heat, electrolisize certain solutions, or do mechanical work. The mechanical work done is due to the reaction of the current and a magnetic field. The effect produced by a current of electricity on a magnet pole is due, not alone to the current, but in addition (1) to the length of the conductor carrying the current; (2) to the inverse square of the distance of every element of the conductor from the magnet pole; and (3) to the strength of the magnet pole.

In order to find the effect of unit current and to satisfy these conditions, there must be (1) a conductor one unit in length; (2) a conductor every element of which is equally and at unit's distance from the magnet pole; and (3) a magnet pole of unit strength. To connect these units to the C. G. S. system, the current must be directed in a conductor one centimetre long, bent into an arc of a circle one centimetre in radius, at the center of which must be placed a unit magnet pole. Satisfying these last conditions, if a current so strong was made to pass along such a conductor that it

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acted on the unit magnet pole with unit force, then that current would be unit current, that is, one electromagnetic unit.

We then arrive at the definition of **unit current** (electromagnetic), as follows: *The unit of current is one of such strength that, if flowing in a conductor one centimetre in length, bent into an arc of a circle one centimetre in radius, it exerts a force of one dyne on a unit magnet pole placed at the point from which the arc is struck.*

A conductor carrying a current and lying in a magnetic field is urged with a certain force across the field, the force being proportional to the length of the conductor and to the strength of the field.

On this consideration, the C. G. S. unit of current exists when *each centimetre of its length is urged across a magnetic field of unit intensity, or one gauss, with a force of one dyne.*

A unit of one-tenth the value of this C. G. S. unit is called the **practical unit of current,** and is the **ampere,** being named for Andre Marie Ampere, a French physicist who lived from 1775 to 1836.

A **milliampere** is a unit one-thousandth of the value of the ampere.

Unit of Quantity of Electricity.

The unit quantity of electricity is that quantity which is conveyed by unit C. G. S. current in one second.

The **practical unit of quantity** is the quantity of electricity conveyed by an ampere in one second. It is equal in value to one-tenth the C. G. S. unit of quantity and is called the **coulomb,** being named for Charles Coloumb, a French mathematician, who lived from 1736 to 1806.

Unit of Electromotive Force (E. M. F.).

If a body is charged with electricity it is said to have a certain potential and is capable of doing work. To charge the body work must be done on it, and this work can be reproduced by allowing the charged body to be connected by a conductor to some other body, when its charge will flow along the conductor and do work. The more work that is done in charging the body the greater is its potential and the more work it is capable of doing.

Difference of Potential.—Difference of potential between two charged bodies is proportional to the difference of work that has been expended in electrifying the bodies. The hammer of a pile-driver that has been raised 20 feet has a certain potential energy. It has the power to do work depending on its height. A certain amount of work has been expended in raising the hammer and this work can be reproduced if it is allowed to fall. A similar hammer that has been raised 10 feet has also a certain potential energy. It has only required half the work to raise it 10 feet as it did to raise the one 20 feet. The difference in the heights of the two hammers represents the difference in the amount of work they can do, and so their potential energies depend on their heights. Similarly, electric potentials may be studied by a consideration of their heights or difference of levels.

The amount of work done in the case of each of the hammers is measured by the height they have been lifted above the earth's surface taken as a common level. So it is convenient to regard electric potentials as being capable of doing work by the degree that they are charged above the potential of the earth, which is regarded as a common level, or zero potential.

Considering as a starting point that the earth is at absolute zero, or neutral potential, a body may be so electrified that it is at a higher potential than the earth, while another may be at a lower potential, depending on the manner they are electrified; or both may be so electrified that they are both higher or both lower than the earth, and yet be at different potentials.

They each have a certain potential and if connected by a conducting medium, an electric current would flow from the one of higher to the one of lower potential, and equilibrium of potential would be established. If the one electrified to a higher potential than the earth be called positive, and it is connected to the earth, there would be a flow of electricity *to* the earth. If the one electrified to a lower potential than the earth be called negative and it is connected to the earth, there would be a flow of electricity *from* the earth. In either case, the potential of the earth would not be changed. The analogy to this is seen in the level of the ocean, which would not be changed if another stream empty into it or a well on land is filled from the ocean.

Electromotive Force.—Difference of potential may be generated in many ways, as by friction, by contact of dissimilar metals, by chemical action, or by magnetic induction. In whatever way produced, the name **electromotive force, E. M. F.,** is given to express the *difference of potential* generated.

If a difference of potential exists between two points, a current will flow from one point to the other, if they are connected by a conducting medium. There will be a gradual *fall* of potential or fall of electric pressure from the one of higher potential to the lower. There is a constant endeavor to equalize the difference of potential and in doing so, electricity flows from one to the other and work is done. If the difference of potential be maintained constant by the continual expenditure of work there will be a constant endeavor to equalization which will result in a continuous flow of current of electricity and continuous electric work.

The constant difference of potential is the total E. M. F. of the circuit, whereas between any two points there is a difference or fall of potential. The sum of all the differences of potential from one point to another around a closed circuit is equal to total fall or total E. M. F.

Fall of potential and total E. M. F. have their analogy in the fall of pressure due to a head of water flowing through restricted pipes.

In Fig. 1 *C* represents a tank filled with water and connected by the column *CB* with a level pipe *AB,* to which are connected vertical pipes *D, E, F, G.* The end of the pipe *A* is fitted with a faucet which may be opened or closed, and *C* is connected to a source of supply so that the level of water in *C* may be kept constant. If at first the faucet at *A* is closed, by a well-known hydrostatic principle, the water will rise in all the pipes until the height in each is on the same level and equal to the height in *C*. The pressure along each portion of *AB* is the same and there is no flow of water. This corresponds to an electric conductor *AB* whose ends are at the same potential; that is, there is the same pressure at each end and, consequently, there is no difference of potential and no movement of electricity.

If now the faucet at *A* is opened and the consequent difference

of water pressure produced between *C* and *A*, water will flow in *AB* and out of each tube, and each level will remain at a height which is determined by the pressure in each tube. If now water is poured into *C* as fast as it flows out from *A*, the level of the water in the several tubes will remain stationary, while the flow of water through *BA* will be constant. Experiment will show that if the cross-section of *AB* is uniform and the tubes are equally spaced from each other there will be an equal difference in the levels of the tubes, and the fall of pressure may be shown by a straight line connecting the level of the water in *C* and end of tube *A*. The

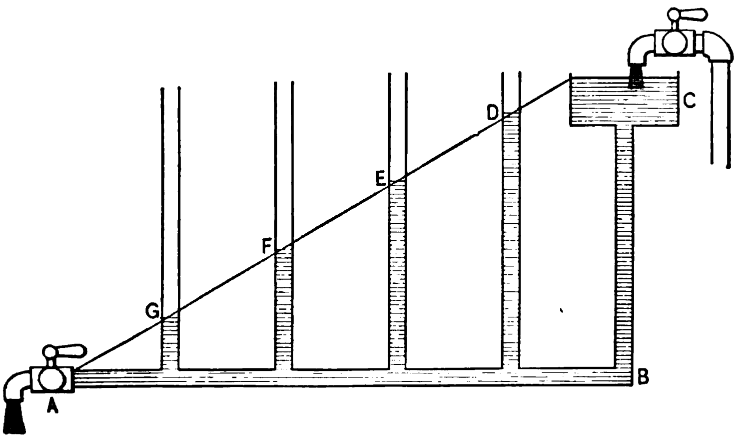


FIG. 1.—Illustrating Fall of Potential.

fall of water pressure is due to the friction of the sides of the pipe *BA* and the fall of pressure is expended in overcoming this resistance.

This is the case of a conductor whose ends are at different potentials. The level in *C* represents the total E. M. F. in the circuit and is kept up by the expenditure of work necessary to keep the height of the water at a constant level. In each section of *BA* there is a drop or fall in potential, and the sum of all the differences from *B* to *A* is equal to the total E. M. F., represented by the total head of water. The fall of potential is expended in overcoming the resistance of the conductor, just as the drop in water pressure was expended in overcoming the friction of the pipe.

If the cross-section of AB is not uniform, the water will stand at different heights such that the fall of the pressure between them will not be regular. The different sections will then offer different amounts of friction, so the fall in pressure will be greater or less. And in the case of the electric conductor, if the resistance through any one particular section is great, the fall of potential will be great. However, whatever the area of cross-section, the same amount of water will flow through each section, flowing more rapidly in the smaller sections, and in the electric current, whatever the resistance, the same amount of current flows through each part of the circuit.

C. G. S. Unit of E. M. F.—Of all the means available for generating E. M. F. that by magnetic induction seems the most logical one on which to base a consideration of the definition of the unit E. M. F. and the one which follows most closely the theoretical conditions.

It is an experimental fact that when a conductor is moved across a magnetic field there is produced in it a tendency to set up an induced E. M. F.

A **magnetic field** is a space or region surrounding magnetic substances, either permanent or temporary, in which magnetic force acts; a space filled with so-called *lines of force,* which by their number at any one place represents the quantity or amount of force and by their direction, the resultant direction of the magnetic force.

The C. G. S. unit of electromotive force is defined to be *that E. M. F. produced by the cutting of a magnetic field of one gauss intensity by one centimeter of the conductor moving at a velocity of one centimeter per second.*

A unit one hundred millions times the value of this C. G. S. unit is called the **practical unit of E. M. F.** and is the **volt,** being named for Alessandro Volta, an Italian physicist who lived from 1745 to 1827.

A **millivolt** is a unit one-thousandth of the value of the volt.

Unit of Resistance.

The application of a steady E. M. F. to the ends of a conductor will produce in the conductor a current inversely proportional to

the resistance the conductor offers to the flow of electricity. *A conductor has one electromagnetic unit of resistance when a steady E. M. F. of one electromagnetic unit applied to it produces one electromagnetic unit of current.* This definition is derived from a consideration of Ohm's law.

Ohm's Law.—This law expresses the relation between E. M. F. current and resistance in a closed circuit in which the current is continuous. It states that the current is directly proportional to the E. M. F. and inversely proportional to the resistance, or in symbols,

$$C = \frac{E}{R}$$

where

$$C = \text{Current},$$
$$E = \text{E. M. F.},$$
$$R = \text{Resistance}.$$

This relation holds in whatever system of units the quantities are expressed, provided they are all expressed in the same system. This law will be more fully dealt with later, and is only introduced here to help explain the unit of resistance. A consideration of the relation existing between the electromagnetic units of current and E. M. F. and the practical units shows that the ohm must be of a value 1,000,000,000 times as great as the electromagnetic unit of resistance. In both systems of units by Ohm's law

$$C = \frac{E}{R}$$

where C, E, and R represent current, electromotive force, and resistance in the two systems. If C', E', and R' represent the values in the practical system of units and C'', E'', and R'' the values in the electromagnetic system, we have

$$C' = 10^{-1}\, C'',$$
$$E' = 10^{8}\, E'',$$
$$R' = \frac{E'}{C'} \text{ and } R'' = \frac{E''}{C''},$$

whence

$$R' = \frac{10^{8}\, E''}{10^{-1}\, C''} \text{ or } R' = \frac{10^{8}}{10^{-1}} R'' = 10^{9}\, R'';$$

or, in practical units, the ohm, the unit must be 10^9 times as great as the value of the electromagnet unit.

A unit 1,000,000,000 times the value of the C. G. S. unit of resistance is called the **practical unit of resistance** and is the **ohm,** being named for George Simon Ohm, a German mathematician who lived from 1789 to 1854, and who was the first to clearly enunciate Ohm's law.

A **megohm** is a unit one million times as great as the ohm.

A **microhm** is a unit one-millionth of the value of the ohm.

Unit of Power.

The C. G. S. unit of power is defined as the rate at which work is being done when one C. G. S. unit of current works under a pressure of one C. G. S. unit of E. M. F.

The **practical unit of power** has a value ten millions times as great as the C. G. S. unit of power and is called the **watt.**

The watt is defined as the rate at which work is being done when a current of one ampere works under a pressure of one volt and is sometimes referred to as the **volt-ampere.**

To connect the watt with the C. G. S. units of power, it is only necessary to substitute the values of the volt and ampere in terms of the C. G. S. units of electromotive force and current, thus

$$1 \text{ watt} = 1 \text{ volt} \times 1 \text{ ampere}$$

and

$$1 \text{ volt} = 10^8 \text{ C. G. S. units of E. M. F.},$$
$$1 \text{ ampere} = 10^{-1} \text{ C. G. S. units of current},$$

or

$$1 \text{ watt} = 10^8 \times 10^{-1} = 10^7 \text{ C. G. S. units of power.}$$

Considering how work in mechanics is defined as the product of a force and the distance moved through due to this force, it is easy to trace the analogy to the derivation of the watt. This is seen in the mechanical work performed by a ventilating fan, the difference of pressure between the entering and leaving orifices forming a current of air, and its power to do work is measured by the difference of pressure produced, and the rate of the moving current of air. The difference of pressure at the orifices corresponds to the

difference of potential of the current, and the air current to the electric current, and their product is the power of the fan, or its rate of doing work. In this connection, it must be recalled that the ampere is not the quantity of current, but rather the rate of flow or quantity in unit time. The total work done in any time would be the number of watts multiplied by the time in seconds.

In order to connect mechanical and electrical units of power, it is sufficient to remember that one mechanical horse-power is equal to 746 watts. This is derived as follows:

$$\begin{aligned}
1 \text{ H. P.} &= 33{,}000 \text{ ft.-lbs. per minute,}\\
&= 550 \text{ ft.-lbs. per second,}\\
1 \text{ ft.} &= 30.48 \text{ centimetres,}\\
1 \text{ lb.} &= 453.7 \text{ grammes,}\\
1 \text{ ft.-lb.} &= 30.48 \times 453.7 = 13{,}828.77 \text{ gramme-centimetres.}
\end{aligned}$$

A gramme-centimetre is the work done in raising one unit of mass, one gramme, one centimetre against the force of gravity. The work done must be the product of force overcome and the distance through which it is overcome. The average force of gravity per unit mass of 1 gramme is 981 dynes, and the work done in lifting 1 gramme 1 centimetre against this force is 981 dyne-centimetres. In the derived mechanical units of the C. G. S. system, the dyne-centimetre is called the **erg**. So when 1 gramme is lifted 1 centimetre against gravity, the work done is 981 ergs, or in other words, 1 gramme-centimetre is equal to 981 ergs.

$$\therefore \qquad 1 \text{ ft.-lb.} = 13{,}828.77 \times 981 \text{ ergs} = 13{,}566{,}029 \text{ ergs,}$$

or

$$1 \text{ H. P.} = 550 \times 13{,}566{,}029 = 7{,}461{,}351{,}900 \text{ ergs per second.}$$

The erg per sec. = the C. G. S. unit of power,

$$\therefore \qquad 1 \text{ H. P.} = 746 \times 10^7 \text{ C. G. S. units of power,}$$

$$1 \text{ watt} = 10^7 \text{ C. G. S. units of power,}$$

or

$$1 \text{ H. P.} = 746 \text{ watts.}$$

The watt was named for James Watt, an English physicist, the inventor of the steam engine, who lived from 1736 to 1819.

A unit one thousand times as great as the watt is the **kilowatt.**

To convert			Multiply by	Divide by
Watts into		H. P.	.00134	746
"	"	ergs per sec.	10^7	
"	"	ft.-lbs. per min.	44.2	
"	"	ft.-lbs. per sec.	.737	
"	"	kilogr.-metres per sec.	.102	9.81
H. P.	"	ft.-lbs. per min.	33.000	
"	"	ft.-lbs. per sec.	550	
"	"	kilowatts	.746	
"	"	watts	746	
"	"	ergs per sec.	7.46×10^9	

Unit of Work.

The C. G. S. unit of work has already been defined. The **practical unit of work** is a unit 10,000,000 times as great as the C. G. S. unit and is called the **joule,** being named for James Prescott Joule, an English physicist, who lived from 1818 to 1889. As heat and work are mutually convertible, it is sometimes referred to as the **electrical unit of heat** and is equal to 10,000,000 ergs. Remembering that the watt is the unit rate of doing work, the number of units of work, or joules, performed in a given time, must be equal to the number of watts multiplied by the number of seconds. The watt was shown to be equal to one volt times one ampere, or

$$W = C \times E,$$

and multiplying by t, we have

$$J = CEt.$$

If $t = 1$ second, the watt is equal to the joule, or the watt may be defined as the work done at the rate of one joule per second. Substituting for E, its value by Ohm's law, $E = CR$,

$$J = C^2Rt.$$

When C, R, and t are all unity, J is unity, and remembering that the joule is the unit of work, expressed as heat, it may be defined *as the heat developed in a conductor in one second by a current of one ampere flowing through a resistance of one ohm.*

The mechanical work equal to one heat unit in the English system of units, for 1° F. is taken to be 778 ft.-lbs., this number being determined by experiment. This means that 778 ft.-lbs. of work, if converted into heat, would raise the temperature of 1 lb. of water at 39° + F. through 1° F. This number 778 expressed in degrees Centigrade becomes

$$\frac{9}{5} \times 778 = 1400 \text{ ft.-lbs.,}$$

or in metric units $\frac{1400}{3.28} = 427$ kilogramme-metres.

This number 427 kilogramme-metres represents the amount of work done equivalent to the work expressed in heat, necessary to raise the temperature of one kilogramme of water at 4° C. to 5° C. and this value expressed in gramme-centimetres is 42,700.

These figures follow from the consideration that

$$\text{No. of degrees F.}^\circ = \frac{9}{5} \text{ no. of degrees C.}^\circ + 32,$$

$$1 \text{ ft.} = \frac{1}{3.28} \text{ metre,}$$

and

$$1 \text{ cm.} = \frac{1}{100} \text{ metre.}$$

In the change of units from one system to another, it is not necessary to consider the change in the unit of mass, as the mass of water that is raised in temperature changes in the same ratio.

Under the watt, it was seen that 1 gr.-cm. was equal to 981 ergs, and therefore the mechanical equivalent in the C. G. S. system is

$$\begin{aligned} 42{,}700 \times 981 &= 4.18 \times 10^7 \text{ ergs} \\ &= 4.18 \text{ joules.} \end{aligned}$$

As the watt is equal to CE or C^2R, and the calorie is equal to 4.18 joules, we have the relation

$$\begin{aligned} 1 \text{ calorie} &= 4.18 \times C^2R \\ &= 4.2 \text{ joules,} \end{aligned}$$

or

$$1 \text{ joule} = .24 \text{ calorie.}$$

This expression is an important one for calculating the rise of

temperature of conductors due to currents flowing in them. The rise in temperature θ° is calculated from the formula

$$\theta^\circ \text{ (Cent.)} = \frac{.24 \times C^2Rt}{ms}$$

where C, R, and t retain their usual significations, and

m = mass of conductor in grammes, and
s = its specific heat.

To convert			Multiply by	Divide by
Watts	into	B. T. U. per sec.	.000954	1,048
"	"	joules per sec.	1	
H. P.	"	calories per sec.	179.4	
"	"	B. T. U. per sec.	.72	

1 H. P. = 33,000 ft.-lbs. per min., and is also equal to 746 watts; therefore,

$$1 \text{ watt} = \frac{33000}{746} = 44.2 \text{ ft.-lbs. per min.,}$$

and the watt being the work at the rate one joule per sec.

$$1 \text{ joule} = \frac{44.2}{60} = .737 \text{ ft.-lbs.}$$

The work in ft.-lbs. done by a current of C amperes flowing through R ohms for t minutes is

$$W = 44.2\ C^2Rt \text{ ft.-lbs.}$$

The number of calories produced by a current C, in resistance R, in time t is

$$H = .24\ C^2Rt.$$

The number of **B. T. U.** produced by a current C, in resistance R, in time t is

$$H^1 = \frac{60 \times .24}{453.9} C^2Rt = .0316\ C^2Rt.$$

The number of joules produced by a current C, in resistance R, in time t is

joules $= C^2Rt$ and
watts $= C^2R$ or, since $CR = E$,
watts $= CE$.

$$
\begin{aligned}
1 \text{ calorie} &= 4.18 \text{ joules} \\
&= 4.18 \times 10^7 \text{ ergs} = 3.086 \text{ ft.-lbs.} \\
&= .00396 \text{ B. T. U.}, \\
1 \text{ B. T. U.} &= 252 \text{ calories} \\
&= 1060 \text{ joules} = 1060 \times 10^7 \text{ ergs} \\
&= 777.7 \text{ ft.-lbs.}, \\
1 \text{ joule} &= .239 \text{ calorie}
\end{aligned}
$$

Examples of Power, Work, and Heat.

1. If 20 amperes flow through a circuit of 10 ohms resistance for an hour, find (1) the heat generated (2) work done in the circuit (3) power absorbed. *Ans.* 3,441,600 calories.
14,400,000 joules.
321.6 H. P.

2. What will be (1) the heat generated (2) work done in a circuit in which a current of 100 amperes causes 50 electrical horse power to be absorbed in 1 hour. *Ans.* 534,882 calories.
2,238,000 joules.

3. Find the potential difference at the terminals of a circuit in which 10 H. P. is absorbed, when a current of 37.3 amperes passes through it. *Ans.* 200 volts.

4. An incandescent lamp of 145 ohms resistance is placed under water in a pail containing 2 kilos of water at 18° C. How long must a current of 2 amperes flow through the lamp in order to raise the temperature of the water to 35° C., provided 98% of the heat goes to raise the temperature of the water.

$$\text{Calories generated} = .24C^2Rt \qquad (1)$$
$$\text{Calories required} = (35\text{-}18) \times 2000 \qquad (2)$$

$$(1) = (2) \text{ or } t = \frac{34000}{2^2 \times 145 \times .24 \times .98} = 249.2^s = 4.15 \text{ min.}$$

5. How much paraffin could be raised in temperature from 10° C. and melted in four minutes by a current of 3 amperes through a wire of 12 ohms resistance imbedded in the paraffin. Sp. heat of paraffin = .2, latent heat = 8, melting point 54° C.

$$
\begin{aligned}
\text{Heat generated in calories} &= C^2Rt \times .24 \\
&= 9 \times 12 \times 4 \times 60 \times .24 \qquad (1) \\
\text{Heat necessary} &= M \times .2 \times (54\text{-}10) + M \times 8 \qquad (1) \\
(1) = (2) \text{ or } \quad M &= 370.3 \text{ grams.}
\end{aligned}
$$

Unit of Capacity.

When an E. M. F. is applied to the terminals of a condenser a certain quantity of electricity will flow into it until it is charged to the same potential as the applied E. M. F. For the present, a condenser may be considered as simply two plates of conducting materials separated by an insulating plate.

In charging such a condenser, current will flow into it only as long as the E. M. F. at its terminals is changing, and a definite change will allow a definite quantity to be held in the condenser. The quality of being able to store this energy is called the capacity of the condenser.

The capacity is defined either in terms of the quantity of electricity which can be held at a certain potential, or in terms of the current which will flow into the condenser when the difference of potential is changing at a certain rate.

A circuit or condenser has a capacity of one C. G. S. unit of capacity when *a rate of change of potential of one C. G. S. unit of E. M. F. per second produces one C. G. S. unit of current,* or a condenser has unit capacity *when it is charged to a potential of one C. G. S. unit by one C. G. S. unit of quantity of current.*

The **practical unit of capacity** is a unit one one-thousand-millionth, 10^{-9}, of the value of the C. G. S. unit of capacity, and is called the **farad**, being named for Michael Faraday, a celebrated English physicist, who lived from 1791 to 1867. A condenser to have the capacity of the farad would be extremely large and a working unit has been adopted, called the **microfarad,** which is one-millionth of a farad.

It may be said that the potential is directly proportional to the charging current and inversely proportional to the capacity. The less the capacity the higher will be the potential for a given current and vice versa.

Example of Capacity.

The E. M. F. in a circuit alternates between 20,000 volts positive and negative, 40 times a second. What current will flow in a conductor if its capacity is 8 microfarads? *Ans.* 12.8 amperes.

Unit of Inductance.

Inductance is the property of an electric circuit by which it resists a change in the current. *When a rate of change of current of one C. G. S. unit per second induces an E. M. F. of one C. G. S. unit, the circuit has unit inductance.*

It will be shown that every circuit carrying an electric current is surrounded by a magnetic field, which is brought into existence by the current. Any change in the current will produce a change in the magnetic field, and this field reacting on the conductor induces an E. M. F. which tends to prevent any change. If the current is increasing, the induced E. M. F. tends to prevent the increase, and similarly when decreasing the induced E. M. F. tends to prevent the decrease.

The induced E. M. F. is directly proportional both to the rate of change of current and to the inductance. The induced E. M. F. acts as a counter E. M. F. to the applied E. M. F. producing the current. If a certain current is flowing in a circuit of certain inductance, the E. M. F. required to reverse it in a given time may be calculated.

The **practical unit of inductance** is a unit of one-thousand millions, 10^9 times as great as the C. G. S. unit of inductance, and is called a **henry**, being named for Joseph Henry, an American physicist, who discovered many of the laws of magnetic induction.

Examples of Inductance.

1. The current in a circuit is changed from 0 to 50 amperes in .005 second. The average induced E. M. F. is 10 volts. What is the inductance of the circuit? *Ans.* 1 Millihenry.

2. How many average volts are required to reverse a current of 50 amperes in a circuit of 5 henries inductance in .5 of a second? *Ans.* 1000 volts.

International or Legal Units.

As a result of an International Congress of Electricians held in 1893, the following units were adopted, these being approved and adopted in June, 1894, by the United States Congress:

1. The **unit of resistance**, the international ohm, which is based

upon the ohm equal to 10^9 units of resistance of the C. G. S. system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grammes in mass, of a constant cross-sectional area, and of a length of 106.3 centimetres.

If the mass of one cubic centimetre of water at 4° C. is one gramme, the area of cross-section of such a column will be one square millimetre.

2. The **unit of current**, the international ampere, which is 10^{-1} of the unit of current of the C. G. C. system of electromagnetic units, and which is represented sufficiently well for practical use by the unvarying current, which, when passed through a solution of nitrate of silver, in water, and in accordance with standard specifications, deposits silver at the rate of .001118 gramme per second.

The anode in the solution is pure silver, the kathode pure platinum, and the liquid is a neutral solution of pure silver nitrate, containing about 15 parts by weight of the salt to 85 parts by weight of water.

3. The **unit of electromotive force**, the international volt, which is the E. M. F. that steadily applied to a conductor, whose resistance is one international ohm, will produce a current of one international ampere, and which is represented sufficiently well for practical use by $\frac{1000}{1434}$ of the E. M. F. between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of 15° C. and prepared in a manner according to standard specifications.

The Clark's cell consists of zinc and mercury in a saturated solution of zinc sulphate ($ZnSO_4$, $7H_2O$) and mercurous sulphate in water, prepared with mercurous sulphate in excess, all held in a small glass jar. The E. M. F. is determined at any temperature $t°$ C. by the formula

$$E = 1.4342\,[1 - .00077\,(t - 15)].$$

4. The **unit of quantity**, the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

5. The **unit of capacity**, the international farad, which is the capacity of a conductor charged to a potential of one international volt by one international coulomb of electricity.

6. The **unit of work**, the joule, which is 10^7 units of work in the C. G. S. system, and which is represented sufficiently well for practical use by the energy expended in one second by an international ohm.

7. The **unit of power**, the watt, which is equal to 10^7 units of power in the C. G. S. system and which is represented sufficiently well for practical use by the work done at the rate of one joule per second.

8. The **unit of induction**, the henry, which is the induction in the circuit when the E. M. F. induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second.

CHAPTER II.

RESISTANCE.

All kinds of matter, whether solid, liquid, or gaseous, offer a resistance to the passage of electricity. An electric current cannot flow unless a difference of electric potential exists, nor can a current flow without encountering some resistance. The definition of the International Unit of Resistance, the ohm, is based on the fact that a certain column of mercury at a certain temperature has a given definite resistance, or it offers at that temperature a certain obstruction to the passage of electricity.

Those substances which offer little resistance to electric currents are called **conductors**, and those which offer great resistance are called **insulators**. Between these extremes are certain substances which are partly conductors and partly insulators and which are called **partial conductors**.

Table of Conductors.

Good Conductors.

Silver,	Lead,	Manganin,
Copper,	Mercury,	Brass,
Aluminum,	Carbon,	Bronze,
Zinc,	Water,	Phosphor Bronze.
Platinum,	German Silver,	
Iron,	Platinum Silver,	

Partial Conductors.

The Body,	Cotton,	Dry wood,	Paper.

Uses of Conductors.

Most of these conductors find some use in the electrical apparatus and instruments installed on board ship.

Copper is used in the dynamo and motor windings, electric light

and power mains, switchboards, bus bars, switches, interior communication circuits, and in general where high conductivity is required and full of potential small. It is particularly adapted for conductors on account of its high conductivity, its abundance, and the ease with which it is worked into various shapes. For conductors it is generally of the wire, ribbon, or bar shape.

Zinc finds its principal use in the anodes of electric batteries.

Platinum conductors are used in incandescent lamps as connecting wires between the copper leading wires and the carbon filaments. Alloys of platinum are used in some forms of rheostats.

Brass or **bronze** finds use for conductors on switchboards, and in the various terminals of dynamo leads on headboards and switchboards and as the interior fittings in water-tight appliances. The conductors, however, for these are copper.

Lead or an **alloy of lead** is used for conductors in the numerous fuses placed in different parts of dynamo or motor circuits to protect the circuits against excessive current.

Carbon is used for conductors in dynamo and motor brushes, in contact pieces for circuit breakers and in the searchlights and arc lamps.

Manganin is used in the resistances of voltmeters and ammeters.

German silver finds use in rheostats, resistance coils, and parts of apparatus where high resistance is required. Its general composition is:

Copper	4 parts.
Nickel	2 parts.
Zinc	1 part.

The variation of the resistance of German silver due to changes of temperature is very small, its coefficient per degree rise in temperature C.° being about nine times less than that of copper. Strong currents continually used in German silver resistances tend to make the conductors brittle.

Phosphor bronze is used in the clips of switches to prevent blisters forming, due to the arc on opening the switch. In some cases it has been used for commutator segments, but they are usually now made of hard drawn copper.

Laws of Resistance.

Experiment shows that the two following laws hold in the case of conductors:

First Law.—The resistance of a given conductor of uniform section at a constant temperature is directly proportional to its length.

Thus if l represents length and R resistance, then R varies directly as l, or

$$R \propto l.$$

If a conductor of a certain length has a certain resistance, then a conductor twice as long, of the same area of cross-section, at the same temperature, will have a resistance twice as great; and if half as long, it will have a resistance half as great.

Second Law.—The resistance of a given conductor at constant temperature is inversely proportional to its sectional area.

If, as before, R represents resistance and a area of cross-section, then R varies *inversely* as a

$$R \propto \frac{1}{a}.$$

If a conductor of a certain area of cross-section at a certain temperature has a certain resistance, then a conductor of twice the area of cross-section, at the same temperature, will have a resistance one-half as great; and if half its area of cross-section, it will have a resistance twice as great.

From a consideration of the above laws, it is seen that R varies directly as the length and inversely as the area of cross-section of the conductor, or

$$R \propto \frac{l}{a}.$$

In order that this equation may give the value of R in ohms and be a pure equation rather than a proportion, it is necessary to multiply it by a *constant* for the particular material of the conductor and temperature at the time.

This constant is called the **specific resistance** of the conductor at the temperature and is defined as *the resistance in ohms of unit length of the conductor having unit cross-sectional area.*

The unit adopted is both the inch and the centimetre, so that the

specific resistance is the resistance in ohms per cubic inch or per cubic centimetre of the conductor, or it is the resistance in ohms between the opposite faces of a cube, either one inch or one centimetre on the side.

Combining the laws of resistance with the definition of specific resistance, we have the fundamental equation of resistance

$$R = \rho \frac{l}{a} \qquad (1)$$

where ρ represents the specific resistance of the conductor at a certain temperature.

Thus the resistance of any conductor may be found if its specific resistance, length, and area of cross-section are known.

In cases where it is inconvenient to measure the length, as in a long coil, it may be weighed and l found from the expression

$$l = \frac{w}{ad} \qquad (2)$$

where w = weight in grammes,
a = area in sq. cm.,
d = specific density,

R then becomes, by substituting the value of l from (2) in (1)

$$R = \rho \frac{w}{a^2 d}.$$

The specific resistance is usually stated in microhms; thus, that of lead is 19.63 microhms, or .00001963 ohms expressed in C. G. S. units.

Table of Specific Resistances.

Substance at 0° C.	Sp. resist. microhms—per cm. cube.	Relative Conductivity.
Copper (annealed)	1.57	100
Copper (hard)	1.60	98
Silver	1.49	105
Platinum	8.98	17
Iron	9.638	16
Lead	19.63	8.3
Mercury	94.34	1.6
Carbon (arc light)	4000	$\frac{1}{2500}$
German Silver	20.76	7.6
Platinoid	30 to 36	
Glass	91×10^{18}	less than $\frac{1}{1,000,000,000}$
Gutta-percha	4.5×10^{20}	same.

Table of Resistances of Chemically Pure Metals at 0° C. in International Ohms.

Name of metal.	Resist. of a wire 1 ft. long $\frac{1}{1000}''$ in diameter.	Resist. of a wire 1 metre long 1 millimetre in diameter.
Silver, annealed	9.0283	.01911
" hard drawn	9.8028	.02074
Copper, annealed	9.5877	.02029
" hard drawn	9.8068	.02075
Gold, annealed	12.3522	.02614
" hard drawn	12.5692	.0266
Aluminum, annealed	17.4825	.037
Zinc, pressed	33.7614	.07145
Platinum, annealed	54.3517	.11503
Iron, annealed	58.308	.12342
Lead, pressed	117.79	.24921
German Silver	125.6139	.26588
Platinum Silver	146.3621	.30979

German silver, an alloy of copper, nickel, and zinc, combined with 1 to 2 per cent of tungsten is known as platanoid. The addition of tungsten gives the alloy greater density and reduces tendency to oxidation. The alloy takes a polish like silver.

Any foreign matter considerably reduces the conductivity of metals and alloys usually show higher resistances than any of their constituents. As a rough unit, a mile of copper wire, $\frac{1}{4}''$ diameter has a resistance slightly less than one ohm.

Relation of Heat and Resistance.

Generation of Heat.—One effect of a current of electricity on a conductor is to produce heat in the mass of the conductor, the number of joules developed being given by the equation C^2Rt. The greater the current, the higher the resistance and longer the time, the greater the increase of heat and consequent rise of temperature.

If the heat is carried away by conduction or radiation as fast as developed its temperature will not rise; or, if after a certain temperature has been attained, the heat is carried away as fast as developed, the conductor will remain at that temperature; but if the heat cannot be dissipated, the conductor will get hotter and hotter until its melting point is reached.

Table of Melting Points.—The melting point of some of the most important conductors are in degrees C.

Alloy, 3 lead, 2 tin, 5 bismuth	93°
Alloy, 1½ tin, 1 lead	168°
Alloy, 1 tin, 1 lead	240°
Tin	230°
Lead	325°
Aluminum	625°
Bronze	922°
Silver	945°
Gold	1045°
Copper	1054°
Cast Iron	1135°
Steel	1380°
Steel, hard	1410°
Wrought iron	1600°
Platinum	1775°

The current that will melt copper wire is given by the formula

$$C = 80d^{\frac{3}{2}}$$

where

C = current in amperes,
d = diameter of conductor in millimetres,

or

$$C = .325d^{\frac{3}{2}}$$

where

d = diameter in thousandths of an inch.

The diameter in inches of a *lead* conductor that will melt with a given current is equal to the cube root of the square of the quotient of amperes divided by 1379. For *half and half* solder the divisor is 1318.

Variation of Resistance with Temperature.—It is to be noted that the table of specific resistances is for materials at a certain temperature, 0° C. This is necessary from the fact that the resistance of any substance, conductor or insulator, depends on the temperature at any given time.

The resistance of all the metals, and with few exceptions of all the alloys, increases with rise of temperature. Non-metals, such as

the solids, carbon, sulphur, silicon, phosphorus, etc., and the principal gases, oxygen, hydrogen, nitrogen, chlorine and its family all decrease in resistance for a rise of temperature. Also the resistance of liquids that can be electrolyzed decreases for a rise of temperature.

Resistance Temperature Coefficient.—The **resistance temperature coefficient** is defined to be *the amount of increase or decrease of resistance in ohms which one ohm in any substance would undergo for each degree Centigrade change of temperature.*

The resistance of conductors increases with temperature in accordance with the following empirical formula:

$$R = r(1 + at \pm bt^2)$$

where

R = resistance at temperature t,
r = resistance at temperature 0° C.,
t = temperature in degrees C.,
a, b = temperature coefficients of the conductor.

It is usually sufficient to disregard the last term and use

$$R = r(1 + at). \qquad \text{(a)}$$

It is ordinarily sufficient to regard t as the difference between any two temperatures, and then r becomes the resistance at the lower and R at the higher temperature.

The temperature coefficient a is positive for all elementary metals except carbon and for most pure metals has an average = .004 between 0° C. and 100° C.

As a general rule, if two or more elements form an alloy, it has a higher specific resistance and lower temperature coefficient than any of its component elements.

The increase in temperature of copper conductors, apart from the increased resistance, is an important factor in calculating the size of conductors to carry certain currents, as they must be large enough to carry their currents without overheating.

Formula (a) may be used to determine the increase in temperature of conductors due to current, by measuring the resistance both when hot and cold. Then knowing the temperature coefficient, the increase in temperature t may be calculated.

The effect of a change in temperature shows that it is important to know the resistance of certain conductors when current is flowing, as the different windings of dynamos and motors, of rheostats, regulators and starting boxes, and particularly it is required to know the *hot* resistance of incandescent lamps, so that the current a lamp is absorbing when it is giving its rated candle-power may be known.

Temperature Correction for Copper Conductors.—A simple formula for finding the resistance of a copper conductor at any temperature is given below.

$$R_t = \frac{LK}{d^2}$$

where

R_t = resistance at temperature t,
L = length of conductor in feet,
d = diameter of conductor in mils,
d^2 = area of conductor in cir. mils,
K = a calculated constant.

K is given in the following table for certain temperatures; the temperatures being calculated from assumed values of K, this being the resistance in ohms of one mil-foot, assuming that the resistance of one mil-foot of pure copper wire is 9.162 ohms at 0° C.

Resistance per mil-foot in ohms K.	Temperature, degrees Centigrade.
10.00	10.26
10.10	12.86
10.20	15.44
10.30	18.00
10.40	20.54
10.50	23.06
10.60	25.56
10.70	28.04
10.80	30.50
10.90	32.95
11.00	35.38
11.10	37.80
11.20	40.20
11.30	42.58
11.40	44.95
11.50	47.30

If the temperature is given in degrees Fahrenheit, it must be reduced to degrees Centigrade by using the formula

$$C = \frac{5}{9}(F - 32).$$

Thus suppose it was required to find the resistance at 64.4° F. of 100 feet of copper wire 4000 cir. mils in area. First reduce 64.4° F. to degrees C. thus

$$C = \frac{5}{9}(64.4 - 32) = 18°.$$

The value of K corresponding to 18° C. is 10.30, so

$$R = \frac{100}{4000} \times 10.30 = .2575 \text{ ohm}.$$

The value of K to be used in the formula is the one that corresponds most nearly to the given temperature; or the exact value for any temperature may be found by interpolation.

Suppose we want to find the value of K corresponding to $t = 36°$ C. The difference in K for a difference of 37.80 — 35.38 = 2.42 t is (11.10 — 11.00) = .1 or for 1t it is $\frac{.1}{2.42}$ and for (36 — 35.38) = .62t the difference is $\frac{.62 \times .1}{2.42} = .0256$, which added to the value of K for 35.38° becomes 11.0256.

Problems on Resistance.

1. Find the resistance at 25° C. of a copper wire 10 metres long and 1 mm. in diameter. The resistance of copper increase by .39% for each degree rise of temperature. Sp. resistance of copper = 1600 C. G. S. units.

$$R_0 = \rho \frac{l}{\pi r^2} = 1600 \times \frac{10 \times 100}{\pi} \times \frac{1}{(.05)^2} = 2.0378 \times 10^8 \text{ C. G. S. units}$$

or $R_0 = \frac{2.0378 \times 10^8}{10^9} = .2037$ ohm

$R_{25°} = .2037 \;(1 + 25 \times .0039) = .2236$ ohm.

2. A uniform glass tube 92.1 cm. in length was filled with mercury and the resistance of the column of mercury was measured and found to be 1.059 ohms. The weight of the mercury contained in the tube was 10.15 grms. Calculate from this experiment the specific resistance of mercury, taking its specific gravity as 13.6.

Ans. 93177 C. G. S. units

3. The resistance of a bobbin of wire is measured and found to be 68 ohms; a portion of the wire 2 metres in length is now cut off and its resistance is found to be .75 ohm. What was the total length of wire on the bobbin?

$$R = \rho \frac{l}{\pi r^2} = 68 \qquad R' = \rho \frac{l'}{\pi r^2} = .75$$

$$\text{or} \quad \frac{l}{l'} = \frac{68}{.75} \qquad l = \frac{200 \times 68}{75} = 181.3 \text{ metres.}$$

4. The resistance at 0° C. of a column of mercury 1 metre in length and 1 sq. mm. in cross-section is called a "Siemens unit". Find the value of this unit in terms of the ohm. Sp. resistance of mercury = 94,-340 C. G. S. units. *Ans.* .9434 ohm.

5. What length of platinum wire 1 mm. in diameter is required to make a one ohm resistance coil? Sp. resistance platinum = 9000 C. G. S. units. *Ans.* 872.8 cms.

Problems on Heat and Resistance.

1. Suppose a chain made of alternate links of silver and platinum, each .2 mm. thick. What current will keep the platinum red hot, 500° C.? What will be temperature of the silver?

Specific resistance of silver = 1.634 microhms; of platinum = 9.957 microhms; radiation per sq. cm. of surface per sec. per degree rise of temperature = .001 joule.

$$\text{Resist. of platinum link} = \rho \times \frac{l}{\pi r^2} = \frac{9.957}{10^6} \times \frac{l}{\pi (.01)^2}.$$

$$\text{Joules radiated per sec.} = \frac{1}{1000} \times 500 \times \pi \times .02 \times l = \frac{\pi l}{100}. \quad (1)$$

$$\text{Joules generated per sec.} = C^2R. \quad (2)$$

$$(1) = (2) \qquad \text{or } C^2 = \frac{\pi l}{100} \times \frac{\pi}{9.957} \times \frac{10^2}{l} = \frac{\pi^2}{9.957}$$

$$\text{or } C = .9956 \text{ amperes.}$$

$$\text{Joules radiated per sec. in silver} = (t - 0) \times \frac{1}{1000} \times \pi \times .02 \times l. \quad (1)$$

$$\text{Joules generated per sec. in silver} = C^2R = (.9956)^2 \times \frac{1.634}{10^6} \times \frac{l}{\pi (.01)^2}.$$

$$(1) = (2) \qquad \text{or } t = \frac{1.634 \times 10^3}{9.957 \times 2} = 82.05° \text{ C.}$$

2. On a certain circuit on board ship there are 15 lamps each taking .7 ampere and a margin of 25% excess of current is allowed. Find the diameter of a lead safety fuse for this circuit. Sp. resist. of lead = 19.85 microhms, melting point 335° C.; loss of heat by radiation and connection per sq. cm. of surface .001 joule per sec. per degree rise of temperature. Initial temperature 18° C.

$$\text{Current allowed for} = 15 \times .7 + \frac{15 \times .7}{4} = 13.125 \text{ amperes.}$$

$$\text{Resistance of fuse} = \rho \times \frac{l}{\pi r^2} = \frac{19.85}{10^6} \times \frac{4l}{\pi d^2}.$$

Joules generated by current per sec.

$$= C^2R = (13.125)^2 \times \frac{19.85}{10^6} \times \frac{4l}{\pi d^2}. \qquad (1)$$

Joules carried away by radiation

$$= \frac{(335 - 18) \times \pi dl}{1000}. \qquad (2)$$

$$(1) = (2) \qquad \text{or } d^3 = \frac{(13.125)^2 \times 19.85 \times 4 \times 1000}{317 \times \pi^2 \times 10^6}.$$

$$d = .1635 \text{ cm.}$$

3. A potential galvanometer has a resistance of 367 ohms and is graduated to show a difference of potential of 100 volts between the terminals. Find the diameter of a lead safety fuse which will melt if the potential difference rises above 100 volts. Temperature of room 20° C., other data as in example 7. *Ans.* $d = .01237$ cm.

4. On a circuit there are 65 incandescent lamps in parallel, each lamp requiring .6 ampere. If a margin of 30% excess of current is allowed, find the diameter of a lead safety fuse to be inserted in the mains. Temperature of room 20° C., other data as in example 7.

Ans. $d = .4034$ cm.

5. If a ward room is supplied with 30 lamps, each taking .8 ampere and a margin of 20% is allowed for, what should be the diameter of a lead safety fuse to protect this circuit? Temperature of room 18° C., other data as in example 7. *Ans.* $d = .2761$ cm.

Temperature Coefficient of a Circuit.

An electrical circuit is ordinarily made up of resistances combined in one or more ways and it will be seen later how the different resistances of a circuit may be combined in *series*, in *parallel*, or in a combination of these, and how the value of the resistances may be calculated.

In certain cases the temperature coefficient of parts of a combined circuit may be required, as when the resistances are made up of conductors of different materials.

Two Resistances in Series.—The case of two conductors of different materials joined in series is shown in Fig. 2.

R_1 and R_2 represent the resistances of the two different conductors joined in series and let a_1 and a_2 represent the temperature coefficients of R_1 and R_2.

The total *increase* or *decrease* of R_1 will be a_1R_1 per 1° C., while that for R_2 will be a_2R_2 per 1° C., and consequently the resistances of each for 1° C. rise will be $R_1 \pm a_1R_1$ and $R_2 \pm a_2R_2$.

FIG. 2.—Two Resistances in Series.

The *combined temperature coefficient,* which is defined as the ratio of the increase or decrease for 1° C. to the original resistance, is called *a,* and

$$a = \frac{R_1 \pm a_1R_1 + R_2 \pm a_2R_2 - (R_1 + R_2)}{R_1 + R_2}$$

or

$$a = \frac{a_1R_1 \pm a_2R_2}{R_1 + R_2} \text{ ohm per ohm per } 1^\circ \text{ C.}$$

If a_1 is positive and a_2 negative, and $a_1R_1 = a_2R_2$ $a = 0$, or the total resistance of $R_1 + R_2$ will be constant at all temperatures, a result of great importance in the construction of certain electrical measuring instruments.

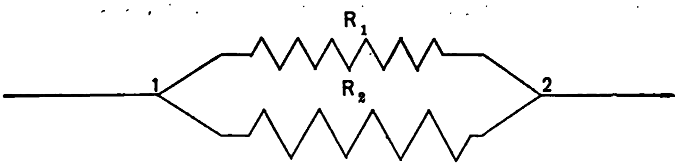


FIG. 3.—Two Resistances in Parallel.

Two Resistances in Parallel.—The case of two conductors of different material joined in parallel is shown in Fig. 3.

As before R_1 and R_2 represent the original resistances of the two conductors of different materials joined in parallel and a_1 and a_2 the temperature coefficients of R_1 and R_2.

It will be shown that the combined resistance of R_1 and R_2 from 1 to 2 is

$$\frac{R_1R_2}{R_1+R_2}.$$

The total increase or decrease of R_1 and R_2 will be a_1R_1 and a_2R_2 per 1° C., and the combined resistance for a change of 1° C. will be

$$\frac{(R_1 \pm a_1R_1)(R_2 \pm a_2R_2)}{(R_1 \pm a_1R_1) + (R_2 \pm a_2R_2)}$$

and the change in resistance due to 1° C. change will be

$$\frac{(R_1 \pm a_1R_1)(R_2 \pm a_2R_2)}{(R_1 \pm a_1R_1) + (R_2 \pm a_2R_2)} - \frac{R_1R_2}{R_1+R_2}$$

and the temperature coefficient for the combined circuit a_1 will be

$$a = \frac{\dfrac{(R_1 \pm a_1R_1)(R_2 \pm a_2R_2)}{(R_1 \pm a_1R_1) + (R_2 \pm a_2R_2)} - \dfrac{R_1R_2}{R_1+R_2}}{\dfrac{R_1R_2}{R_1+R_2}}$$

and this reduces to

$$a = \frac{(R_1+R_2)(1 \pm a_1 \pm a_2 \pm a_1a_2)}{R_1+R_2 \pm a_1R_1 \pm a_2R_2} - 1 \text{ ohm per ohm per } 1^\circ \text{ C.}$$

Conductivity.

Conductivity is the name given to express the ease with which substances conduct electricity. A substance of high conductivity has low resistance and vice versa, and conductivity is the reciprocal of resistance.

The **unit of conductivity** is called the **mho**, and is the reciprocal of the ohm. It is the conductivity of a conductor whose resistance is one ohm.

A consideration of the laws of resistance will show that similar laws hold for conductivity, and are embraced in the formula

$$K = \frac{a}{\rho l}.$$

The *specific conductivity* is the conductance between opposite faces of a cube, one inch or one centimetre on the side.

Resistance of Series and Parallel Circuits.

As previously stated, electric circuits consist of conductors of various resistances connected in one or more ways to form one or more complete paths for the flow of the electric current, and the combined or total resistances of the various branches depend on the manner in which they are joined.

There are two main systems of arranging conductors, called **series system** and **parallel system**, and a complete circuit may be of a complex system of either or a combination of both.

Resistances in Series.—Conductors are joined in series, when the end of one is connected to the end of another, all in one line, or connected *end on* to one another, as indicated in Fig. 4.

FIG. 4.—Resistances in Series.

Any current that flows from A to B must flow through each of the several resistances in turn, and the same current must flow through them all. The resistance of one is additive to another and it is plainly evident that the total resistance of any number of separate resistances connected in series is equal to the sum of their separate resistances. Thus the resistance from A to B is

$$R_1 + R_2 + R_3 + R_4 + R_5 .$$

It is also evident that it matters not in what order the resistances are joined, as the addition of each resistance is a positive increase to the total resistance.

Resistances in Parallel.—Resistances are connected in parallel when one or more branches of the circuit are connected to the same points of the circuit. This is illustrated in Fig. 5.

Three resistances R_1, R_2, and R_3 are connected to the same points of the circuit, at A and B and it is required to find the combined resistance of the three, or the resistance of a single conductor joining A and B that would allow the same current to flow in the circuit to which A and B are connected.

The *conductance* of R_1 is $\frac{1}{R_1}$ and similarly for R_2 and R_3, and it is evident that the conductance from A to B is the sum of the conductances of the various branches, or the total conductance from A to B is

$$K=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$$

and as the total conductance is the reciprocal of the total R,

$$K=\frac{1}{R},$$

or

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$$

and

$$R=\frac{R_1R_2R_3}{R_1R_2+R_1R_3+R_2R_3}.$$

If

$$R_1=R_2=R_3$$

$$R=\frac{R_1}{3}=\frac{R_2}{3}=\frac{R_3}{3}.$$

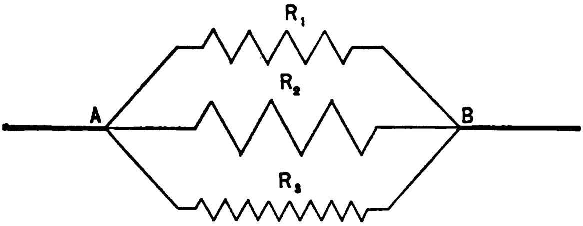


FIG. 5.—Resistances in Parallel.

As there are now equal paths for the current to flow, it is the same as though the three resistances had been replaced by one of three times the cross-sectional area, and it has been shown that resistance varies inversely as the area, so if the area is three times as great as one, the resistance would be one-third of each of the conductors.

Resistances in Series and Parallel.—The most common arrangement of conductors in an electrical circuit is a combination of the series and parallel systems as indicated in Fig. 6.

The resistance from A to B of such a circuit is the sum of all the resistances of the several parts, thus from A to B is equal to resistance from A to C + that from C to D + that from D to B, and as above, total resistance is

$$R = R_1 + \frac{R_2R_3R_4}{R_2R_3 + R_2R_4 + R_3R_4} + R_5 .$$

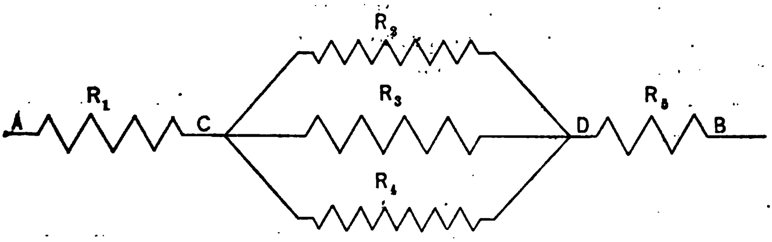


FIG. 6.—Combined Series and Parallel Resistances.

Resistance of Joints and Imperfect Contacts.

When two dissimilar conductors are joined together either by binding screws or soldering, and a current passed from one conductor to the other, their junction will be either heated or cooled, dependent on the direction in which this current is flowing. Conversely, if this junction be either heated or cooled, a current will be set up, flowing in a direction dependent on the material of the conductors. This heating effect is very small and does not arise from any resistance the current meets at the junction of the conductors. It is simply mentioned in order to distinguish it from the resistance that all joints do give rise to, some more than others.

It is impossible to compute what is the extra resistance added to a circuit due to imperfect joints or contacts, the resistance varying with the goodness or poorness of contact. It should be seen that all joints and connections are perfectly tight, for the less nearly perfect they are, the greater the resistance, the more heat developed in them and consequently more energy uselessly wasted. Loose joints in an electric-light circuit will often cause a fluttering of the lights, and many causes may be sought, when it is only such a little thing as a loose connection on the switchboard.

One form of a rheostat is composed of carbon blocks, which by varying the pressure on them alters the resistance of their contacts and so alters the current in the circuit.

Insulation.

Insulation is defined as the means adopted for preventing electric currents from acting along any other path than through the conductors provided for the purpose. Insulators are simply substances which are poor conductors of electricity, though even the best insulator has some conductivity, just as the best conductors have some resistance.

The amount of electricity which insulators allow to pass through them is called the **leakage**, and this takes place through the whole cross-section of the insulation, and along the film of moisture on the outside surface of the insulation.

Dirt and moisture act against good insulation, and whenever possible insulators should be highly polished to prevent dirt from sticking, and they should be coated with some form of non-absorbent to prevent the formation of moisture.

The resistance to leakage is obviously the resistance of the insulator, and is given by the same formula as resistance of conductors,

$$R = \frac{\rho l}{a}.$$

Therefore, the longer the insulator and the smaller the area of cross-section, the greater the resistance, or the more efficient the insulator.

Properties of Insulators.—The first requisite of all insulators is of necessity high insulation resistance. This should be combined with waterproof and fireproof qualities, and with toughness and flexibility. For use with high potentials, insulators should have sufficient dielectric strength to prevent rupture from sparking.

Heat affects very materially the insulating properties of substances and in some cases it may alter the chemical composition of insulating compounds. The insulation of some substances change with the degree of electrification, in which cases, heat has a greater

effect. In testing the insulation of electrical conductors the resistance is not measured until at least a minute has elapsed after the conductor is charged.

Table of Insulators.

Oils,	Wool,	Resin,	Glass,
Shellac,	Silks,	Mica,	Air.
Varnish,	Rubber,	Paraffin,	
Porcelain,	Cotton,	Ebonite,	

Uses of Insulators.

Rubber.—Some form of rubber, either gutta-percha, India rubber, pure rubber, or vulcanized rubber is universally used as the principal insulation for copper conductors. Hard rubber is used for washers in the disc or cylindrical form, for switch handles, rheostat arms, and the bases of instruments. The ease with which it can be pressed or molded into shape makes it particularly useful for many purposes. All bushings through bulkheads or beams are made of hard rubber.

Porcelain is used in certain forms of rheostats with the conductors imbedded in it, and for the bases on which rest interior fittings of wiring appliances. Many washers are made of porcelain or some form of earthen ware and used under screw heads or bolts. Porcelain, marble, or slate is used for the foundation of switch-boards and panel boards. It is also used for insulators to carry cables where conduit or molding is not used.

Mica is used for the insulation between segments of the commutator of dynamos and motors, in wiring appliances under the fittings, and for covers of fuse boxes.

This is an excellent insulator; does not deteriorate with high temperature and has a high resistance to sparking, and is also practically non-hygroscopic. It can be made in thin sheets or built up in layers of any desired thickness, and can be made pliable by interposing insulating varnish made from shellac or resin between sheets.

Cotton is used in the form of thread on conductors and in the piece for insulation of certain parts of armatures, particularly the conductors and on the core.

Shellac is used where a light insulation is required and in connection with other insulators. It is rarely used by itself and is generally used as an outside covering to prevent the accumulation of moisture. Armature laminations are insulated with shellac.

Paraffin is used to cover the resistance coils in resistance boxes, offering at the same time good mechanical protection, as it is put on in the liquid state and covers all parts of the coils.

Glass is used as the dielectric for condensers used in wireless telegraphy sets.

Oils are used for insulation where high potentials are carried. The secondary coils of induction coils and certain glass-plate condensers used in wireless telegraphy outfits are often contained in receptacles which are filled with oil.

Different kinds of **paper, cardboard,** or **pressboard** are for armature insulation.

Okonite or some form of rubber forms the base of many insulating tapes and is applied to cotton tape.

A very good flexible insulation, with fairly high resistance, can be made by heating fibrous material with linseed or other oil, drying and finally thoroughly baking it.

Vulcabeston, a mixture of rubber and asbestos, is a very good insulator and satisfies most of the requirements. It is unaffected by high temperatures, does not absorb moisture, is very hard and strong, and has high dielectric strength.

CHAPTER III.

PRIMARY BATTERIES.

Batteries, defined as combinations of electric cells, are of two general classes, primary and secondary or storage batteries. Of these two general classes, the former is the only one that has found any extensive use on board ship, though even its uses are constantly being curtailed by means of current from the dynamos. They are still used for bell work, telephone circuits, for firing guns and torpedoes and for exploding electric mines.

Primary Cells.

Electric cells all generate electricity by chemical action and the term cell is applied to an arrangement in which one or more substances forming a fluid or dry mixture act upon two different metals, or a metal and carbon placed in the mixture, whereby a difference of potential is produced between the metals, a condition necessary to the performance of electric work.

If a piece of metal is placed in a fluid called an electrolyte, there is at once produced a difference of electrical condition of such a kind that the metal either takes a higher or lower potential than the fluid. If two pieces of different metals are placed in the electrolyte, a condition may be produced of one metal assuming a higher potential than the liquid and the other a lower, in which case if the two metals are connected by a conductor outside the liquid, there will be a current of electricity established. The current proceeds from the metal which has a higher potential than the liquid, or the metal which is most actively acted upon chemically by the electrolyte.

Simple contact of dissimilar metals will give rise to a difference of potential, and all metals may be arranged in a table so that any one element in the list will be electropositive to any one below it;

or, in other words, will be of an absolute higher potential than any below it when they are placed in contact. One being electropositive to the other means that if a current flows it will be *from* the one which is electropositive to the other.

Table of Electrochemical Series.

1. Aluminum,	7. Tin,	13. Platinum,
2. Manganese,	8. Copper,	14. Carbon,
3. Zinc,	9. Hydrogen,	15. Chlorine,
4. Iron,	10. Mercury,	16. Oxygen.
5. Nickel,	11. Silver,	
6. Lead,	12. Gold,	

In this table the difference of potential caused by the contact of any two elements is equal to the sum of the differences of potential caused by the contact of all the elements that are between them in the list. Thus the difference of potential caused by the contact of zinc and lead is equal to the sum of the differences caused by the contact of zinc and iron, iron and nickel, and nickel and lead.

Electrolyte.—The electrolyte must be a substance that will act chemically upon at least one of the elements placed in it, and it may be either a chemical acid or a chemical salt. The object of the electrolyte is to increase the difference of potential between the elements placed in it, and by chemical action to keep the difference of potential constant, so that when the electric circuit is completed, a continuous current may be the result.

The real source of energy seems to be in the element that is acted upon most actively chemically, the other element acting as a hand dipping into the liquid to gather and direct the electric current. The electric energy is represented by the wasting away or the consumption of the element of high potential, and the real starting point of the current is at the surface of this element.

Simple Examples of Electrochemical Action.

An examination of the table of electrochemical series shows that iron is electropositive to copper, so that if these two metals are in direct contact, a difference of potential arises causing a current that

will be represented by the wasting away or pitting of the more electropositive one, iron. If these two elements are brought in contact by salt water, we have all the elements for a simple galvanic cell, and the effects of this combination are plainly shown in some copper-sheathed ships, the iron near the sheathing becoming pitted and eaten away. The same effect is seen in the pittings of copper pipes in the salt-water system, the pitting of the copper being due to the fact that copper is electropositive to the chlorine in the salt water. Where copper pipes come through the side of iron ships, it is usual to separate them by zinc rings, so that the zinc-copper combination will prevail over the iron-copper combination and the zinc will be consumed rather than the iron. These zinc plates may be renewed from time to time so as to protect the iron.

Definitions.

The following general definitions apply to all single cells:

The **cell** is the shell, cup or vessel that contains the elements and the exciting fluid. It may be made of glass, porcelain, earthenware or metal.

The **plates** are the elements, metal or carbon pieces that dip into the electrolyte, and are generally referred to as the *electrodes.*

The **electrolyte** is the liquid or dry mixture which acts chemically on the electrodes. In general it is a liquid that is decomposed by a current passing through it.

The **poles** are the portions of the electrodes that project from the electrolyte.

The **terminals** are mechanical devices by which conductors are secured to the poles.

The electrodes are distinguished by one being called positive +, the other negative —, the positive one being the one coming first in the Table of Electrochemical Series.

The **anode** is the positive electrode, the one at which the chemical action is the greater and is the plate by which the current enters the liquid.

The **kathode** is the negative electrode and is the one by which the current leaves the liquid.

It should be noted that the positive pole is part of the negative plate, and the positive terminal is on the positive pole, while the negative pole is part of the positive plate and the negative terminal is on the negative pole.

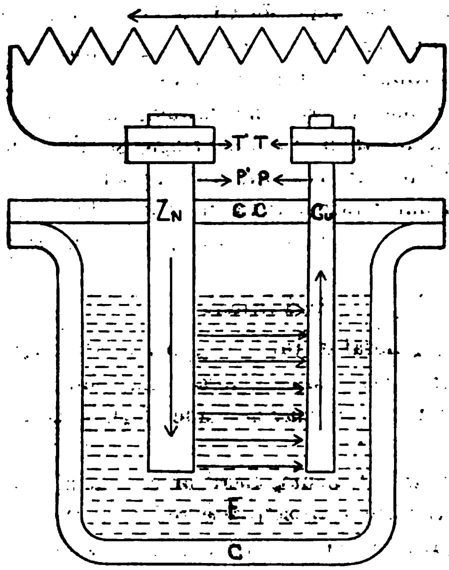


FIG. 7.—Typical Primary Cell.

T = + terminal,	Zn = zinc strip,
T' = — terminal,	= + plate,
P = + pole,	= + electrode,
P' = — pole,	= anode;
CC = cell cover,	Cu = copper strip,
C = cell,	= — plate,
E = electrolyte (exciting fluid),	= — electrode;
	= kathode.

These definitions are illustrated in Fig. 7, showing a simple typical cell with its outside conductor.

The term *cell* is also applied to the whole combination, the cell, electrolyte, electrodes and terminals.

Polarization.

This is the name given to express the weakening of the current when the circuit is closed, due to internal action in the cell, and is generally caused by the collection of bubbles of gas on the kathode. By the chemical action, which takes place between the electrolyte and the anode, gases are liberated from the former and the bubbles are carried across the electrolyte and deposited on the kathode. All gases offer great resistance to electricity, the result being that the current is much weakened, and in some cases polarization almost prevents any current from flowing. If the gases are electronegative to the kathode, they tend to set up an E. M. F. opposed to the original E. M. F. thus still further reducing the current.

Polarization is gotten rid of in three different ways: (1) by mechanical, (2) by chemical, and (3) by electrochemical means; the latter preferably by using a second substance separated from the electrolyte, or by a solution in the electrolyte which will absorb or enter into chemical composition with the liberated gases.

The *depolarizer* is the substance used to prevent or counteract polarization and may be either a solid or a liquid.

Local Action.

This is a name given to the chemical action that goes on in a cell when the circuit is open, that is when the outside circuit is broken. This is a quiet action and is usually due to impurities in the electrodes. It ordinarily arises from particles of iron, arsenic or other foreign metals in the anode, which in most forms is zinc. These impurities being imbedded in the zinc and the zinc and impurities in contact with the electrolyte form little closed circuits which gradually waste away the zinc. It is obviated by using chemically pure zinc, but as this is very expensive, by amalgamating the zinc, that is by giving it a slight coating of mercury. The mercury covers up the impurities and seems to bring only the pure zinc to the surface. The amalgamated surface seems to hold a film of hydrogen gas which acts to protect it from local action at all times.

Electromotive Force of Cells.

As has been stated, the E. M. F. of a cell depends entirely on the electrodes and the electrolyte used. In the contact of dissimilar metals, the difference of potential is due alone to the elements themselves, and not to their size, shape, or other characteristics, and this holds true in an electric cell as far as the E. M. F. is concerned, though the resulting current depends very much on the size, shape, and distance apart of the electrodes.

E. M. F. on Open Circuit.—When the circuit is open the difference of potential between the poles is always equal to the total E. M. F. developed within the cell; or, in other words, the E. M. F. of a cell is the difference of potential between its poles when no current is passing through or from it. When the circuit is closed, the E. M. F. at the poles is less than the total E. M. F. due to the volts lost in driving the current through the internal resistance of the cell, and this point must always be borne in mind in connecting up cells for any particular work.

By Ohm's law, the loss of potential in the cell itself is equal to the current flowing through the cell multiplied by the internal resistance. So if E is the total E. M. F. of a battery due to the battery itself, C the battery current, and r the internal resistance, then the loss of potential or lost volts in the cell is Cr and the available difference of potential at the terminals $E' = E - Cr$.

To measure directly the total E. M. F. of a battery or cell, it must be compared with the E. M. F. of some standard cell, but to obtain the E. M. F. of this standard cell, it must be measured electrostatically by some means, for in all other ways, there must be current drawn from the cell and this will vitiate the result.

Measurement of E. M. F.—The E. M. F. of a cell may be measured directly by means of Sir Wm. Thompson's absolute electrometer, which draws no current whatever from the cell. The principle of this instrument is that of a condenser with one fixed and one movable plate. If these two are connected to two points of an electric circuit, between which there exists a difference of potential, the movable plate tends to move so as to increase the electrostatic capacity of the condenser, and it is moved with a force

proportional to the square of the difference of potential by which the force is produced. The force produced is measured by balancing it against known weights. An ordinary condenser with a galvanometer and key in circuit may replace the electrometer, when comparing the cell with some standard cell.

There are many laboratory ways of comparing E. M. F., all of them requiring some standard cell, or cell whose E. M. F. is accurately known, certain known resistances and a galvanometer. Galvanometers are not furnished on board ship, but a very good substitute may be found in a double reading voltmeter furnished on some ships as a ground detector, and the resistances of the Wheatstone bridge may be used. These will be described later, and having these, one method will be described showing how the E. M. F. of a cell may be compared with one whose E. M. F. is known.

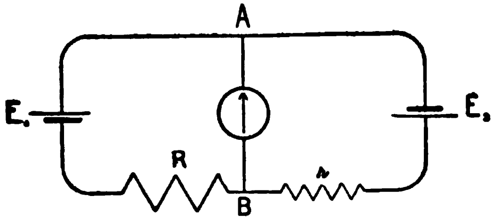


FIG. 8.—Connections for Comparing E. M. F. of Cells.

The two batteries or cells to be compared are joined up as shown in Fig. 8, their opposite poles being connected by leading wires and resistances *R* and *r* being inserted in one side of the connections, the points *A* and *B* being connected by a galvanometer or the double reading voltmeter. If the resistance *R* is fixed, then *r* is adjusted until the voltmeter shows no deflection; or, in other words, *A* and *B* are at the same potential. When this condition holds then

$$E_1 : E_2 :: R : r$$

from which the E. M. F. of either cell may be found in terms of the other.

The resistances of the leading wires are supposed to be inap-

preciable and the resistances of the cells small in comparison with R and r, but if not, they must be added to R and r (see Chapter VI).

This method is easily arranged and comparison of cells may be made in a very short time. For all practical purposes, however, the E. M. F. of a cell is sufficiently determined by connecting its terminals to the binding posts of a low-reading portable voltmeter. The small curent flowing from the cell is inappreciable owing to the high resistance of the voltmeter, so that the lost volts in the cell are extremely small and the E. M. F. as measured is very near the total E. M. F. of the cell.

Resistance of Cells.

By the resistance of a cell is meant the resistance it offers to the flow of electricity, measured from terminal to terminal, and is the sum of the resistances of the separate parts that go to make up the internal circuit. It is a physical characteristic depending on the elements of which the electrodes are made, of the exciting fluid, and of the depolarizing substance, solid or liquid. The resistance of the electrodes may be reduced by making them in the form of plates, by which a large surface is exposed to the exciting fluid, and the resistance of the electrolyte may be reduced by shortening the path the current in it has to follow. This is done by bringing the electrodes close together, and in some forms, one electrode entirely surrounds the other. The resistance of liquids is high as compared with metals, and that of gases still higher. The resistance of the gases liberated by the chemical action is the chief cause of polarization in a cell, increasing the resistance to such an extent that the current rapidly falls off. This resistance due to the gases is not properly a part of the cell resistance, and being a variable quantity is not included in the internal resistance.

In one method for measuring battery resistance, the battery is inserted as the fourth arm in the Wheatstone bridge, and its ordinary position is taken by leading wires with a key K in circuit. The principle and application of the bridge will be shown later, it being sufficient at this time to simply state methods and results.

The resistance a should be as low as possible and b high. With the key K open (Fig. 9) current will flow through the galvanometer and a deflection of the needle will occur. If on making and breaking the key K, there is no change in the deflection, the points where the leading wires are connected to the bridge must have the same potential. When this is the case and there is no change in the deflection, the following relation holds:

$$B = \frac{aR}{b}.$$

R should be 1000 ohms if possible, b 10,000 ohms, and then a will usually be less than 20 ohms. b should be adjusted until there is

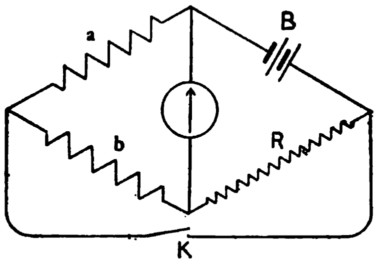


FIG. 9.—Connections for Measuring Resistance of a Cell.

no change in the deflection, but if a change always occurs when the key is opened or closed, determine two values of b, one of which increases, the other decreases the deflection, and take the value which gives the least change.

The galvanometer should be connected between the junction of the two highest and two lowest resistances.

NOTE.—For derivation of the above formula, see Chapter VI.

Resistance of a Working Battery.—When a battery is working through an external resistance and a certain current is being drawn from it, the internal resistance may and will probably be different from its resistance on open circuit, and it is frequently of importance to know what the working resistance is. A sufficiently accurate method for determining this is as follows: With a volt-

meter (see later) measure the difference of potential between the terminals of the battery when on open circuit; call this E_1. Make the same measurement when working through the external resistance and call this E_2, and this should be made before polarization sets in.

When a current is flowing, part of the total E. M. F. is expended in sending current through the external resistance and part through the battery resistance, but only E_2, the fall of potential through the external circuit can be measured, and $E_1 - E_2$ is the fall of potential through the battery; therefore, by Ohm's law, where r is the internal resistance of the battery,

$$C = \frac{E_1 - E_2}{r} \text{ and } C = \frac{E_2}{R},$$

or

$$r = \frac{E_1 - E_2}{E_2} R.$$

If an ammeter (see later) is connected in the circuit, it is not necessary that the value of R should be known, as

$$r = \frac{E_1 - E_2}{C}.$$

When two known resistances are available, r can be calculated as follows: With the resistance R_1 in circuit, measure E_2 and C_1 and with R_2 measure E_2 and C_2, then

$$C_1 = \frac{E_2}{r + R_1} \text{ and } C_2 = \frac{E_2}{r + R_2}$$

and

$$r = \frac{C_2R_2 - C_1R_1}{C_1 - C_2}.$$

Grouping of Cells.

Knowing the E. M. F. and internal resistance of the cells with which one has to work, and the character of work to be done, it becomes important to know which is the way to group cells in order to get the best results. It may be that high E. M. F. is desired or a large current, or the greatest current may be wanted, or the most economical working may be sought. There are three

principal ways of arranging cells, namely, in **series**, in **multiple arc** or **parallel**, and in **multiple series**.

Series Grouping.—Cells are connected in **series** when the positive electrode of one is connected with the negative electrode of another, and the positive one of this to the negative of the next and so on, the number so connected being referred to as so many in series. This arrangement is shown in Fig. 10.

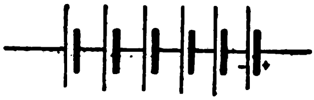


FIG. 10.—Cells in Series.

The effect of such a grouping is to sum up all the electrical and mechanical effects of each cell; that is, the total E. M. F. is the sum of the individual E. M. F's. of each cell, and the total resistance is the sum of the internal resistances of each cell. If the cells have the same characteristics, then this total E. M. F. is the E. M. F. of one multiplied by the number of cells, and the total resistance, that of one multiplied by the number of cells.

By Ohm's law, for a single cell

$$C = \frac{E}{r + R}.$$

Where

C = current in circuit,
E = E. M. F. of the cell,
r = internal resistance of the cell,
R = external resistance in circuit.

With a number of cells m, connected in series,

$$C = \frac{mE}{mr + R}.$$

If there is no external resistance, that is, if the battery terminals are short-circuited, $R = 0$ and

$$C = \frac{mE}{mr} = \frac{E}{r},$$

or the current is no more than if there was one cell with its terminals short-circuited.

If R is very small compared with mr, $C = \frac{E}{r}$, or the current is that of a single cell.

If mr is small compared with R, $C = \frac{mE}{R}$, or in this case the current increases with the number of cells.

Cells connected in series are used on work in which R is already large, so that any increase in the internal resistance is not of much moment, the increased E. M. F. producing increased current.

Multiple Grouping.—Cells are grouped in **multiple arc**, or **parallel**, when all the positive electrodes are connected, and all the negative electrodes connected, or all the positive electrodes are connected to one common conductor and all the negative electrodes to another common conductor. This arrangement is shown in Fig. 11.

The effect of this grouping is to practically make one big cell, for as was shown under the electromotive force of batteries, the difference of potential is due to the electrodes themselves. In the case of the five cells shown, the effect is to make two electrodes each five times as large as that in a single cell and, therefore, the total E. M. F. due to these cells grouped in multiple arc is the same as that due to one cell. In this arrangement, there are now five paths for the current to follow in the battery; or, in other words, the total resistance of these five cells is only one-fifth that of each cell. Or, considering two electrodes each five times as large as that of a single cell, the resistance of each large electrode would be only one-fifth of that of each cell.

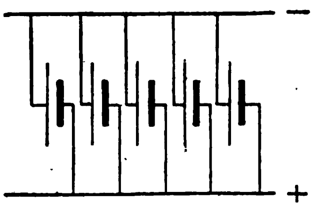


FIG. 11.—Cells in Parallel.

If there are n cells connected in multiple arc, and the resistance of each is r, the total resistance of the n cells is $\frac{r}{n}$, and the total current through the battery, neglecting the external resistance would be

$$C = \frac{E}{\frac{r}{n}} = \frac{nE}{r}.$$

This arrangement, therefore, increases the current, without increase of E. M. F. and is used where a strong current is required with low E. M. F. or for external work in which the resistance itself is low.

Multiple Series Grouping.—Cells are grouped in **multiple series** when some are connected in series, and the groups connected in series are grouped in multiple arc, as shown in Fig. 12.

Here are shown ten cells, groups of two being connected in series and five groups of two in series being connected in multiple arc. The effect of this grouping is to give an E. M. F. double that of one cell, with an internal resistance of one-fifth of the resistance of the two cells in series, or two-fifths the resistance of one cell, assuming they are all alike.

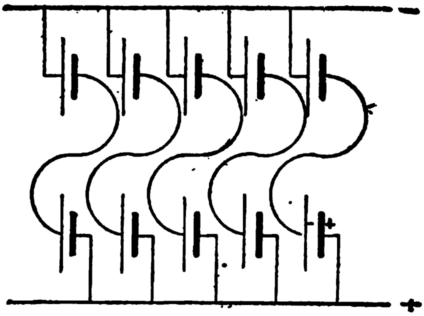


FIG. 12.—Cells in Multiple Series.

In general if there are m cells connected in series and n groups of m cells each connected in multiple arc, the resulting battery current, neglecting external resistance would be given by

$$C = \frac{mE}{\frac{mr}{n}}$$

where C, E, and r have the same significance as before. The total external current through a given resistance R would be

$$C = \frac{mE}{\frac{mr}{n} + R}.$$

It should be noted that the current through each group in series, and consequently through each cell, would be $\frac{C}{n}$.

For most battery work, some modification of this system is used, depending on the difference of potential and current required. It is used also when a higher E. M. F. and stronger current are required than any one cell would give.

Best Arrangement and Efficiency of Batteries.

a. *To find the best arrangement of a given number of cells* (N) *to obtain the maximum current* (C) *through a given external resistance* (R).

In addition to the symbols and significations already used, let

$m =$ the number of cells in series in each group,

$n =$ the number of series groups in multiple.

It can be mathematically shown that the current has its greatest value when the internal resistance of the battery is equal to the external resistance in circuit, that is, when

$$\frac{m \times r}{n} = R.$$

$$\text{Total current} = \frac{\text{total E. M. F.}}{\text{total resistance}}$$

$$C = \frac{mE}{\frac{mr}{n} + R}.$$

Since

$$N = m \times n, n = \frac{N}{m} \text{ and } m = \frac{N}{n}.$$

Substituting the value of

$$n = \frac{N}{m} \text{ in } \frac{mr}{n} = R$$

we have

$$\frac{m^2 r}{N} = R \text{ or } m = \left(\frac{NR}{r}\right)^{\frac{1}{2}},$$

and similarly

$$n = \left(\frac{Nr}{R}\right)^{\frac{1}{2}}.$$

This enables us to know how many cells to put in series and how many groups to put in parallel to get the greatest current, R and r being known.

b. To find the greatest current which can be obtained from a given number of cells (N) through a given external resistance (R).

As before

$$C = \frac{mE}{\frac{mr}{n} + R},$$

$$\frac{mr}{n} = \left(\frac{NR}{r}\right)^{\frac{1}{2}} \times \left(\frac{R}{Nr}\right)^{\frac{1}{2}} \times r = R,$$

or

$$C = \frac{\left(\frac{NR}{r}\right)^{\frac{1}{2}} \times E}{2R} = \frac{E}{2}\left(\frac{N}{Rr}\right)^{\frac{1}{2}},$$

an equation in which all the quantities are known to solve for C.

c. To find the number of cells in series (m) and number in parallel (n) required to give a current (C) through an external resistance (R) and to have an efficiency (F).

By the *efficiency* of a battery is meant the ratio between the total work available in the external circuit and the total work developed by the battery. The total work developed by the battery is the product of the total E. M. F. and total current (see Joule and Watt), and the total available work is the product of the total external current and the fall of the potential through that circuit.

If $e =$ fall of potential through external circuit

$F =$ efficiency,

then $$F = \frac{eC}{EC} = \frac{e}{E},$$

but $e = CR$ and $E = C\left(R + \frac{mr}{n}\right)$.

$$\therefore \quad F = \frac{R}{R + \frac{mr}{n}},$$

or the smaller the internal resistance r, the greater is F.

From

$$F = \frac{R}{R + \frac{mr}{n}},$$

we have

$$\frac{mr}{n} = \frac{R(1 - F)}{F},$$

and substituting this value in the equation for current we have

$$C = \frac{mE}{\frac{mr}{n} + R} = \frac{mEF}{R},$$

or

$$m = \frac{CR}{EF} \text{ and } n = \frac{Cr}{E(1-F)}.$$

d. To find the efficiency of a battery arranged (m) in series and (n) in parallel through an external resistance (R).

There are always two values for the efficiency (F) for any particular number of cells (N).

$$N = m \times n = \frac{CR}{EF} \times \frac{Cr}{E(1-F)} = \frac{C^2Rr}{E^2F(1-F)}$$

or

$$F = \frac{E(N)^{\frac{1}{2}} \pm (NE^2 - 4C^2Rr)^{\frac{1}{2}}}{2E(N)^{\frac{1}{2}}}.$$

This gives two values for F except when

$$NE^2 = 4C^2Rr.$$

Substituting in this the value of $N = mn$

and $$C^2 = \frac{m^2E^2F^2}{R}$$

it reduces to

$$4F^2 = R \times \frac{n}{mr}.$$

Now when $R = \frac{mr}{n}$ we have the greatest current, and then

$$4F^2 = 1 \text{ or } F = \tfrac{1}{2} \text{ or 50 per cent.}$$

This means that when the cells are so grouped as to cause the greatest current, the battery is doing work at its greatest rate, but it is only working at an efficiency of 50 per cent, or only 50 per cent of the total work is being utilized, the rest being absorbed in the battery itself.

Economical Working.—As far as the cost is concerned the most economical grouping would be that which would give the least consumption of materials, which in most batteries would mean the consumption of the zinc, by the consumption of which the chemical action is kept up.

The weight of zinc used is given by the formula $w = Czt$, where

w = weight in grammes of zinc consumed,
C = current in amperes,
z = electrochemical equivalent of zinc,
t = time in seconds.

w is evidently directly dependent on C, so the most economical working would be when C is the least, which would virtually be the case when the cells are all grouped in parallel.

Examples of Grouping of Cells.

1. What arrangement of 24 cells, each of E. M. F. 1.3 volts and resistance 2 ohms, will send the greatest current through an external resistance of 13 ohms?

For greatest current, the internal resistance must be equal to the external resistance.

Let $m =$ the number of cells to be grouped in series.

$n =$ the number of series groups to be placed in parallel.

$m \times n =$ whole number of cells.

$\frac{mr}{n} =$ internal resistance, $13 =$ external resistance,

or

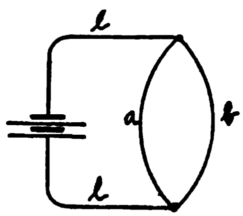
$\frac{2m}{n} = 13$ $mn = 24.$

$\therefore \quad m = 12$ $n = 2.$

2. What is the best arrangement to give the greatest current from 12 cells, E. M. F. of each 1.8 volts and resistance 5 ohms. The external resistance consists of an instrument .5 ohm resistance, of the leading wires .25 ohm resistance, and two electrolytic cells, one of 4 ohms resistance and the other of 3 ohms. *Ans.* $m = 4.$
$n = 3.$

3. A battery of 40 cells is to be so arranged that it will send the maximum current through an external resistance consisting of two branches, connected to the battery by two leading wires, one of resistance of 2 ohms, the other of 2.5 ohms. One branch has a resistance of $6\frac{2}{3}$ ohms and contains 4 fuses in series, each of 1 ohm resistance, and the other has a resistance of 11 ohms and contains 7 fuses in series, each of 3 ohms resistance. *Ans.* $m = 10.$
$n = 4.$

4. A circuit is arranged as in the figure. The branch *a* is composed of 10 fuses in series and *b* of 15, each fuse having a resistance of 1 ohm and requiring .75 ampere to fire it. The leading wires have a resistance of 3 ohms. How should a battery of 36 cells, each having an E. M. F. of 1 volt and resistance .25 ohm be arranged to give the maximum current through the fuses? *Ans.* all in series.



5. Twelve cells, each of which has an E. M. F. of 1.9 volts and resistance .28 ohm are to be coupled up so as to develop the greatest possible amount of heat in a copper wire of .21 ohm resistance. How must this be done? *Ans.* No. of groups in parallel, 4.
No. in series in each group, 3.

CHAPTER IV.

TYPES OF PRIMARY BATTERIES.

Batteries for use on board ship are generally confined to one or two classes, the Leclanché type being in general use for call, telephone, and alarm circuits, and some form of dry cell used for firing guns, torpedoes, or mines. The use of cells for bell circuits is gradually being curtailed by the dynamo current and an illustration of how this is accomplished will be given later, but the cells in ordinary use will be described.

Leclanché Cell.

There are several types of this cell to be found, but their general characteristics are the same, differences arising from the manner in which the electrodes and depolarizer are made up, this last making a difference in the resistance of the various types.

The positive electrode, or anode, is zinc, as near chemically pure as possible, and some forms being amalgamated. This is generally in the form of a round strip not unlike a lead pencil in shape. The negative electrode, the kathode, is carbon and in different types, this is made up in different shapes, and it is this difference that makes the various types of this cell. The exciting fluid is ordinary clean water in which is dissolved the chemical salt, ammonium chloride, or the sal ammoniac of commerce. The depolarizer is a paste made of peroxide of manganese, a black powder, mixed with powdered graphite. In the earlier forms, the carbon was imbedded in this paste which after treatment became hard, and the whole filled a porous earthenware cup that stood in the sal ammoniac solution. The porous cup was found to increase the resistance of the cell and another form was adopted. In this the depolarizer is in the form of hard blocks and these are secured to the carbon

plate, one on each side, by rubber bands, and then the whole is placed in the exciting fluid, in which the zinc simply stands.

In another form of this battery, notably in the Samson and Hayden types, the carbon is made in the form of a hollow cylinder and the depolarizer is placed inside the cylinder. The cell is an ordinary glass jar, coated a short distance from the top with paraffin to prevent the salts that are formed from "creeping" over the top, and covered with a hard rubber top, through which the terminals of the electrodes project.

Chemical Action in the Cell.—The action that goes in the cell is represented by the following chemical formula:

$$aC + b(MnO_2) + c(NH_4Cl) + dZn = aC + (b-2)(MnO_2) + (c-2)(NH_4Cl) + Mn_2O_3 + 2NH_3 + H_2O + ZnCl_2 + (d-1)Zn.$$

The current is primarily produced by the action of the ammonium chloride on the zinc, the zinc gradually wasting away as shown in the formula and the salt zinc chloride being formed. It is the double salt of this chloride that collects on the electrodes and on the sides of the cell and sometimes works its way over the edges of the cell. Free ammonia gas is evolved from the ammonium chloride which escapes or is dissolved in the liquid. Hydrogen is liberated from the ammonium chloride, and this would soon cause depolarization were it not for the manganese peroxide. Under the chemical action, this salt gradually gives up oxygen and part of it is converted into another manganese salt, Mn_2O_3. The oxygen thus liberated unites with the hydrogen freed from the ammonium chloride, to form water, thus getting rid of the chief cause of depolarization. As shown by the formula, the zinc gradually wears away while the carbon remains unchanged.

In one form of this cell, the E. M. F. is about 1.48 volts with an internal resistance of 4 ohms, though these values vary in the different types. It gives a quick current for a short time, but its great advantage lies in the fact that on open circuit it recovers itself so quickly. It runs down quickly owing to the formation of the hydrogen bubbles, but part of the action goes on when the circuit is open, the hydrogen uniting with the oxygen. This quick recovery

makes it particularly useful for bell work, where the current is not steady or continuous but intermittent.

With ordinary care a good Leclanché cell should last for years, and by this is meant keeping the cells clean, free from accumulation of salts on the electrodes, and taking precautions to keep the liquid from splashing over as the ship rolls. The battery locker should be kept free from dust and be in a cool, dry location. Above all, it should be seen that there are no short circuits when the circuit is open, as this would soon destroy the usefulness of any cell.

Sal Ammoniac Solution.—Different classes of cells of the Leclanché type require different strengths of solution to get the best results, but an average solution is about five ounces of dry ammonium chloride (sal ammoniac) to one quart of water. If the solution is too strong the double chlorides of zinc and ammonium are liable to crystallize and be deposited on the zinc, increasing the internal resistance and lowering the E. M. F.

Effect of Double Chlorides.—There is generally more or less of the double chloride of zinc and ammonium present in every sal ammoniac cell. This is heavier than the solution of zinc chloride and ammonium chloride and sinks to the bottom of the cell. Zinc in a zinc chloride solution is positive to zinc in a solution of the double salt, the result of which is a local action which tends to dissolve the zinc at the top and deposit it at the bottom. The cell is practically short-circuited on itself and this explains why almost all zincs in this class of cells grow thinner at the top first. Near the surface there is a slight oxidation process which also tends to thin the zincs.

Firing Batteries.

Different forms of batteries are used for firing guns, illuminating the night sights of guns, and for firing torpedoes and submarine mines. The general form adopted for firing guns and torpedoes is a dry cell similar in its electrical conditions to the Leclanché type. Some forms used are known commercially as "Roach Standard Dry Cell," "O. K. Cells," "Harrison Electrolyte Jelly Cells." The "Dry Cell" is furnished in two sizes, the small dry cell and the large dry cell.

In the dry cell, the cell itself forms the anode, being made of zinc to which is soldered the terminal. The kathode is a carbon slab imbedded in a dry paste which fills the whole cell. Next the zinc cup is a layer of powdered ammonium chloride mixed with lime, inside of which is a powdered mixture of graphite and manganese dioxide in which the carbon is imbedded in the center of the cell. The carbon projects over the top of the cup to which the terminal is secured. After the paste is packed in around the carbon and fills the cell, the whole is sealed with pitch to prevent the access of moisture and for mechanical protection. There is a small hole left in the pitch through which a small amount of water may be added if necessary and to allow the escape of gases.

The E. M. F. of the small cell, dry, is 1.5 volts with an internal resistance of not over .3 ohm, while the large cell has an E. M. F. of 1.5 volts and a resistance of not over .15 ohm.

Standard Cell.—The cell now used as a standard is one similar to the "Navy Reserve Cell," Type FFF, as manufactured by the National Electrical Supply Co. of Washington, D. C. This cell is entirely similar to other dry cells described above with the exception of the active material which is furnished in a perfectly dry state. The cell itself is of zinc which forms the anode and to which the terminal is secured. The cell is lined with an inactive material, and dry ammonium chloride and manganese dioxide in a powdered state fills the space in the cell between the zinc anode and the carbon kathode in the central portion. This latter is made in the form of a cylindrical tube perforated with holes. The upper portion of the carbon is fashioned like the neck and mouth of a bottle, to which the terminal is secured and in which fits a cork. The active material is kept intact by a layer of pitch, and the outer surface of this, as well as the neck of the carbon which protrudes through the pitch, are coated with a layer of paraffin.

In the dry state there is not intimate contact of the active materials and the cell is inert, but is rendered active by the addition of water through the mouth of the carbon. This makes a paste of the ammonium chloride, sal-ammoniac, and of the depolarizer, manganese dioxide, and brings all into close contact. One cell requires about a gill of water. This cell should give about 1.5 volts and 10

amperes of current. The specifications for this cell require dimensions of 7¼" high × 2½" diameter and when charged to show at least 1.45 volts at the terminals, measured with circuit closed through a resistance of 25 ohms at the end of 3 minutes.

Common Batteries.

Although the Leclanché type of cell is used almost to the exclusion of all others on shipboard, the following table may be useful as giving the characteristics of some of the standard common cells:

STATISTICS OF CELLS.

Class.	Name.	Anode.	Electrolyte.	Kathode.	Depolarizer.	E.M.F.	Remarks.
Mechanical depolarizer.	Volta.	Zinc.	Sulphuric acid (dilute).	Copper.	None.	.9	Polarizes rapidly.
Same.	Smee.	Zinc.	Sulphuric acid (dilute).	Platinized silver.	None.	1 to .5	Same.
Chemical depolarizer.	Bunsen.	Zinc.	Sulphuric acid (dilute).	Carbon.	Nitric acid.	1.9	Kathode and depolarizer in porous cup.
Same.	Grove.	Zinc.	Sulphuric acid (dilute).	Platinum.	Nitric acid.	1.9	Same.
Same.	Leclanché.	Zinc.	Ammonium chloride.	Carbon.	Peroxide of manganese.	1.48	High resistance about 4 ohms.
Electro-chemical depolarizer.	Daniell.	Zinc.	Zinc sulphate.	Copper.	Copper sulphate with crystals.	1.07	Kathode and depolarizer in porous cup.
Same.	Chloride of mercury.	Zinc.	Ammonium chloride.	Carbon.	Paste of mercurous paste.	1.45	Same. For small currents.
Same.	Chloride of silver.	Zinc.	Ammonium chloride.	Silver.	Silver chloride.	1.03	Used for testing.
Same.	Latimer Clark.	Zinc.	Paste of mercurous sulphate with zinc sulphate.	Mercury.	Electrolyte.	1.442	Standard cell for very small currents.

CHAPTER V.

SECONDARY BATTERIES.

Secondary batteries are combinations of secondary cells, or as they are sometimes called, accumulators or storage cells. A secondary cell is an electrochemical transformer of energy. In a primary cell, the elements are active chemically in themselves and produce electrical energy by chemical decomposition, and when the constituents are entirely decomposed, the cell is dead, and can only be made active again by a fresh supply of its constituents. A secondary cell can be made active by the passage of a current in the opposite direction to that which the cell itself develops.

Typical Secondary Cell.

The principle of the secondary cell may be studied by the action of a current on lead plates immersed in a solution of dilute sulphuric acid. Although these lead plates are identical, one may be considered positive and the other negative, and the one by which the current enters the cell is called the **positive** plate, or **anode,** and the other the **negative** plate, or **kathode.** In its original state, such a combination cannot produce an electric current, for whatever chemical action takes place between one lead plate and the acid is counteracted by the chemical action between the other plate and the acid.

If a current from an outside source is sent through such a combination, in a short time oxygen gas is liberated from the water in the acid solution and passes to the anode and unites chemically with the lead of the plate to form a chemical compound, lead peroxide, PbO_2. Due to this compound, the anode turns a brownish color. Hydrogen gas is also liberated from the water in the acid solution by the passage of the current and collects on the kathode, but no chemical action takes place. The water in the

solution which is thus gradually decomposed slowly disappears and the solution becomes more strongly acid.

On stopping the outside current, the cell is now in a different electrical condition, and in the place of the two original lead plates, there is now one plate of lead peroxide, PbO_2, and one of lead, Pb, in the electrolyte of sulphuric acid, H_2SO_4. This is now capable of acting like a primary cell and generating current by the difference of potential existing between the two plates; chemical action being set up if the plates are connected outside the cell. The acid will now act chemically on the plate of lead peroxide, and current will result, and in time, both plates will become of the same chemical composition and the current will cease. This is now a secondary cell and can store up the energy given to it until it is required to be used, and can be revived without using any fresh chemicals, by simply passing a current through it.

Elements of Cells.

Cells proper can be made of glass, metal, wood lined with glass or pitch or celluloid. For stationary work glass is the best, but for movable batteries, other forms are chosen.

The electrolytes used may be alkaline, acid, or neutral, and the materials are very numerous, depending on the plates employed.

The plates may be all metallic, or one set may be of metal and the other of carbon, and in some cases neither is metal.

Planté Cells.

The earliest reversible cells were those of the Planté type, developed by M. Gaston Planté about 1860. They differ only from the typical cell described in that the lead plates are made porous, either by mechanical or chemical means. Some are cast porous, others are built up of lead ribbon, and most of them of different makes are treated with nitric acid before being used in the cell.

The positive and negative plates are identical at the start. They have lugs cast on them to project above the level of the electrolyte so that the plate may be completely immersed. A strip of lead is then soldered to the lugs of those intended to be positives and a

similar strip to those intended to be negatives for one cell. The two sets of plates are then pushed into one another to form a compact block, positive and negative alternately, each plate being insulated from the next one by some non-conductor, as India rubber bands, blocks, vulcanite, etc., but remain joined by the lead strips. Such a block of plates is held together by rubber bands or a wooden frame, and the *section*, as it is called, is ready to be placed in the electrolyte.

A battery of cells is now made by connecting the cells in series, and the whole is ready for *forming*.

This forming consists in sending an electric current through the cells for a long time, with the result, that, notwithstanding both positive and negative plates start identical in their composition, after a time they alter their chemical composition, and soon become capable of retaining a charge; that is, a good primary battery is obtained with reversible properties.

The **capacity** is the amount of energy in ampere hours that the cell after charge is capable of delivering.

Frequent reversals are necessary to obtain good capacity and it takes a long time before the maximum capacity is reached, and by that time the plates become disintegrated. A *reversal* is made by completely discharging the cells through a resistance, then charge again the reverse way, then discharge and again charge, etc.

Although this type of cell has points in its favor, such as the fact that a large charging current or rapid discharge does not much injure the plate, yet it is handicapped by the laborious forming process necessary, and has been superseded by a class of cell known as the **Faure** type.

Faure Cells.

In order to increase the output capacity, and to obviate the long and costly process of making a cell by Planté's method, Faure in 1880 suggested pasting the lead plates with easily reducible oxides of lead.

Cells of this type are therefore known as *pasted* cells. The pasted plate is made in many ways but the result sought in all is the same;

that is, to produce a porous leaden or other support carrying paste. The paste is carried in holes of different shapes made in the plates, which are made of porous lead or an alloy of lead, for strength.

The anode or positive plate while being charged (the positive pole at discharge), is usually pasted with a stiff paste of red lead, minium (Pb_3O_4), and sulphuric acid, and the kathode or negative plate is pasted with a mixture of litharge, lead monoxide (PbO), and sulphuric acid. The result of each of these pastes is to really form the plates into lead sulphates ($PbSO_4$). After the plates are pasted they are allowed to harden, and are then built up in sections as previously described.

The cells are now connected in series and a current passed through them for a long time, causing the paste on the positives to become converted into lead peroxide, PbO_2, and the paste on the negatives becomes reduced to finely divided spongy lead.

During the *forming* process, the positives become a plum or chocolate color, while the negatives obtain a yellowish tint on the surface and pale slate color at the edges.

Chemical Action in Forming.

When minium is treated with sulphuric acid in the preparation of the paste for the positive plate, the following reaction takes place:

$$Pb_3O_4 + 2H_2SO_4 = PbO_2 + 2PbSO_4 + 2H_2O.$$

The treatment of litharge with sulphuric acid preparatory to pasting the negative plate gives rise to the following:

$$PbO + H_2SO_4 = PbSO_4 + H_2O.$$

Therefore, before forming, the positive is pasted with a mixture of PbO_2 and $PbSO_4$, and the negative with $PbSO_4$. These plates are now immersed in sulphuric acid solution of specific gravity 1.18. If the oxides, in preparation of the pastes had been mixed with some inactive medium instead of sulphuric acid, the acid used in the cell should be that whose specific gravity is 1.21. Due to the difference of potential between PbO_2 and $PbSO_4$ the electromotive force of each cell is about 1.7. In *forming*, for the first long charge,

a current of about 10 amperes is passed through each cell for from 48 to 60 hours, when the following reactions take place:

Positive plate—$PbSO_4 + O + H_2O = PbO_2 + 2H_2SO_4$.

Negative plate—$PbSO_4 + 2H = Pb + H_2SO_4$.

The H_2SO_4 liberated from the insoluble $PbSO_4$ mixes with the electrolyte and the specific gravity gradually rises until when the charging is complete it reaches 1.21.

One of the important tests for completeness of forming is that the specific gravity becomes constant and fails to rise above this point for 2 hours of continuous charging, tests being taken every fifteen minutes.

The voltage of each cell before charging is stopped should be nearly 2.5, but when the charging current is stopped this soon falls to 2.2. The excess of voltage is caused by the hydrogen deposited on the negative plate after the latter has been completely reduced to metallic lead, and after it has passed off the true difference of potential between Pb and PbO_2 in the H_2SO_4 is shown.

NOTE.—In writing the reactions for charging and for discharging it may be convenient to consider the water of the electrolyte to be decomposed, hydrogen going in the same direction as the current, and oxygen in the opposite direction.

There is an additional action which goes on during forming or charging, as gas is given off at all periods of the charge, first off the positives only and later off the negatives. This would seem to indicate that water is being decomposed, and that the O does not act upon the paste of the positives as readily as does the hydrogen upon that of the negatives. When the end of the forming approaches, the negatives can absorb no more gas and H is given off from these plates.

Charging of Cells.

The operation of charging the cells is that of *forming* as previously described, as far as it relates to the chemical action. When *formed* or charged, the positive plate has been changed to lead peroxide, PbO_2, and the negative to spongy, metallic lead, Pb, both

being in finely divided form and thus furnishing large surface for action and hence decreasing the resistance of the cell.

As charging proceeds, the specific gravity of the acid increases, and its conductivity increases, or its resistance diminishes. The original solution should be about a 20 per cent solution of pure acid; that is, the mixture should contain about four parts of water to one of acid, and on being fully charged, the solution will be about a 25 per cent solution. Sulphuric acid is a good conductor and water a bad conductor, so, on charging, as the acid strength increases the resistance decreases. If this were not so, the charging current would grow rapidly less as the end of the charge approached.

A well-charged cell has about half the resistance of a discharged one, due to the greater conductivity of the electrolyte and to the fact that the plates are better conductors when charged.

It has been stated under the operation of forming that gases are given off and the operation is not unlike that of boiling. As the surface of the positive plates becomes changed into lead peroxide, the material to be acted upon by the current grows less and less, and consequently the current is excessive to do the work and the gases from electrolysis are given off very freely. This can be obviated by lowering the current, or stopping it altogether for a time and then starting it, when it will be noticed that the bubbling does not immediately recommence. Water should be added from time to time to keep the plates well covered, and the proper specific gravity of the acid should be kept up by the addition, if necessary, of more strong acid.

If too large a current is used for the area of the plates, *buckling* is apt to occur, due to heating, and short circuits in the electrolyte may result through the plates touching. Buckling is due to unequal expansion of the plate and as the paste expands on discharge the expansion and contraction should be symmetrical, or the paste is apt to loosen from its supports.

The plates in each cell should be so arranged that the resistance from all parts of one plate to every portion of the adjoining one should be equal, and if not, buckling is apt to take place. All

connecting strips should be large and short and the junctions should be clean and tight to reduce the resistance.

Discharging of Cells.

On the discharge of a cell, the reverse chemical action takes place from that on forming or charging. The chemical actions are thus represented:

$$\text{Positive plate—}PbO_2 + 2H + H_2SO_4 = PbSO_4 + 2H_2O.$$

$$\text{Negative plate—}Pb + O + H_2SO_4 = PbSO_4 + H_2O.$$

Current passes within the cell from the Pb to the PbO_2 along with the hydrogen of electrolytes.

This shows that the cell returns to its original state and in the meantime has stored up the energy of the charging current. The action also goes on slowly when discharge is not taking place and the cell is idle. The gradual loss of charge is somewhat similar to the local action that goes on in a primary cell. The lead peroxide and the lead decompose the acid, producing $PbSO_4$, and the local action of the positive plate will be more active if there is but a thin coating of the peroxide.

The rate of discharge depends upon the type and size of plate; but the discharging current can be larger than the charging current. There should always remain about 25 per cent of the total charge the cell is capable of taking, and the moment that the E. M. F. falls below an average of 1.8 volts per cell, the battery should be charged. In testing for this, not the whole E. M. F. should be tested, but each single cell should be tested with a low-reading voltmeter, which should be carefully calibrated, as a small error might make considerable trouble. If in any cell the E. M. F. falls to 1.7 volts or below it needs charging, or if the others are up, this one should be cut out of circuit.

When the plates are nearly discharged nearly all the paste on the positives is in the form of $PbSO_4$ and this will soon decompose into higher sulphates which ruin the plates or cause them to buckle when charging. Too rapid a discharge buckles the plates and very sudden discharges loosens the paste, even though the current may

be well within its limit, and current should be drawn slowly from the battery until it reaches the maximum desired. Not more than 25 per cent of the maximum should be suddenly drawn from the plates.

If from any cause a cell in the battery becomes dead, it should be immediately cut out, for on discharging, the current will charge it the wrong way, which will reduce the effective E. M. F. of the battery by twice its voltage as well as soon ruin the cell, due to the formation of sulphates, buckling, and the loss of paste.

Effect of Specific Gravity of Solution on E. M. F.

The E. M. F. of a lead sulphuric acid cell varies with the specific gravity of the acid of a charged cell, but averages about 2 volts per cell. For a variation in voltage for 1.7 to 2.1 volts the specific gravity variation is from 1.18 to 1.20, and between these limits, the variation of voltage is gradual, but outside the limits the voltage varies much more rapidly than the specific gravity.

Capacity and Output.

Practically the only limit to the current which a secondary cell will give is the resistance to which it is connected, as the internal resistance of the cell itself is very low, in some cells amounting to a few thousandths of an ohm. A short circuit of low resistance may produce such a high current that it may cause the acid to boil and spatter, may burn the contacts or produce buckling of the plates or even cause them to fuse.

The current that can safely be taken from a cell depends on the type of cell and the total area of the positive plates, counting both sides, and is rated as so many amperes per square foot, and in different types and makes may vary from 5 to 25 amperes per square foot.

The capacity of a cell is rated in either **ampere hours** or **watt hours**, meaning that the cell can be discharged at a certain rate of current for so many hours, whose product will equal to the output in ampere hours.

Efficiency.—The efficiency is the ratio of output to input and

$$\text{Quantity efficiency} = \frac{\text{ampere hours given out}}{\text{ampere hours put in}}, \text{ and}$$

$$\text{Energy efficiency} = \frac{\text{watt hours given out}}{\text{watt hours put in}}.$$

Types of Secondary Cells.

Many patents have been taken out for secondary cells, but they may be generally classified in three classes:

1. Those in which the active element is formed from the substance of the plate itself.

2. Those in which the active element is formed from some reducible lead salt applied to the plate.

3. Those in which one element of class 1 is employed for one plate and class 2 for the other.

Chloride Secondary Cell.—This type of cell presents some peculiarities in the construction of the plates, chloride of lead being used in the manufacture of the negative plates. The chemical properties of the positive plate resemble the cells of the Planté type, though the mechanical method of construction is different. For purposes of rigidity, an alloy of lead and antimony is run into molds, and these are so constructed that there are round holes in them, closely spaced, each hole tapering from the outside faces towards the center. These holes are filled with rosettes of pure lead, and they are forced under great pressure into the countersunk holes.

The plates are then formed by coupling them alternately with dummy negative plates in sulphuric acid, and passing a current through, when all the interstices of the pure lead rosettes are filled with a fine coating of lead peroxide, PbO_2.

In the manufacture of the negative plates, pellets of lead chloride $PbCl_2$ are first made, and they are assembled on the plate molds, which are provided with pins over which the pellets slip. Molten lead is then run into the molds under pressure. The cast plates containing the pellets of $PbCl_2$ are then placed alternately

with zinc plates in a bath containing a solution of $ZnCl_2$ and short circuited, when the following reaction takes place:

$$PbCl_2 + Zn = ZnCl_2 + Pb$$

and the pellets become spongy lead.

When they are connected up with the positive plates with sulphuric acid and charged, the hydrogen evolved combines with the last trace of chlorine from the pellets and leaves them pure spongy lead.

The $PbCl_2$ used above is formed by treating known quantities of lead oxide, PbO, with acetic acid, $C_2H_4O_2$. From this, acetate of lead is produced which is treated with hydrochloric acid, HCl, and which precipitates all the lead acetate as lead chloride,

$$Pb(C_2H_3O_2)_2 + 2HCl = PbCl_2 + 2C_2H_4O_2.$$

The $C_2H_4O_2$ is separated from the solution by forcing it through a filter press while the $PbCl_2$ is left behind in the form of white paste cakes. This is then dried and mixed with a small percentage of finely divided metallic zinc and this mixture is heated to a very high temperature and it becomes a fluid. This fluid is then poured into molds the shape of the pellets.

Edison Alkaline Cell.—In this cell the positive active material consists of a finely divided high oxide of nickel, and the negative material of finely divided iron with an electrolyte of a solution of potassium hydrate. The active materials are mixed with graphite and molded under pressure into thin cakes. The plates are made of nickel steel, in which are slots for holding the cakes which are also enclosed in thin covering of nickel steel.

On discharge the iron oxidizes while the nickel oxide is reduced to a lower oxide. A full description is given later.

Regulation of Voltage at Discharge.

Since the voltage of a cell may vary from about 2.2 volts at the beginning of discharge to 1.8 volts at the end, a number of cells in series will produce a widely varying voltage unless some regulating means are provided to compensate for the fall in voltage when in discharge during a considerable period.

The simplest method is to use a resistance in the battery circuit but this is objectionable because of the waste of energy.

A common method is to have in addition to the regular battery a number of extra cells so arranged that when in discharge the voltage of the battery falls, these cells may be switched in one at a time in series and in this way keep up the total electromotive force of the battery. These cells are called **end cells.** The terminals of these cells are connected to contact points arranged in a circle over which moves a contact arm, which by moving one way or the other acts to raise or lower the total voltage by varying the number of cells in series.

In switching from one point to the next, the circuit must not be opened, for the switch contacts would suffer by sparking due to excessive induced current, nor must the contact arm touch two adjacent contacts as this would short circuit the cell to which these terminals are connected. The end cell switches are provided with an auxiliary contact either on the movable arm or fixed near each main contact. The main and auxiliary contacts are joined by a resistance, and the auxiliary contact rests on one of the switch contacts while the main contact touches the adjoining point. By this means the circuit is not broken, being completed through the resistance which has too low a value to affect materially the line potential, but is sufficiently great to prevent the cell from being short circuited.

Series and Parallel Charging.—In the case of most pasted plates as received from the manufacturers, the forming process consists of a long, continuous charge, lasting over a period from 48 to 60 hours, and should continue until the specific gravity of the acid solution shows no increase for several hours, nor the voltage of any cell shows an increase for the same time. The hydrometer is a better indication of the state of charge than a voltmeter, though both should be used.

When the plates are first placed in the acid solution a difference of potential of 1.6 to 1.7 volts will be given at the terminals of a cell. At the end of the first charge, each cell should show approximately 2.5 volts and the specific gravity of the solution should attain its highest value.

The source of charging voltage must be at least slightly greater than the voltage of the whole battery, calculated on a basis of 2.5 volts per cell. Thus, if a battery of 50 cells is to be charged in series, a source of at least $50 \times 2.5 = 125$ volts must be available. The smaller the difference between the charging voltage and the counter E. M. F. of the battery, the smaller would be the charging current, and consequently the longer time it would require to charge it.

If the source of voltage is not sufficient to give the proper charging current against the counter E. M. F. of the battery, the battery may then be charged in two parallel rows by doubling the total charging current. Thus, suppose a 110-volt circuit was available to charge 50 cells and the desired charging current was 10 amperes; the 50 cells could be divided into two groups of 25 each, making a maximum counter E. M. F. of $25 \times 2.5 = 62.5$ volts. On first starting the charge, the counter E. M. F. would be $25 \times 1.7 = 42.5$ volts, and with a 10-ampere current, a resistance of $\frac{110 - 42.5}{20} =$ 3.37 ohms would have to be inserted in the charging line; the 20 amperes dividing, so that each half of the battery would take 10 amperes each. As the counter E. M. F. increased, the inserted resistance would have to be reduced to keep the charging current constant. After being charged in parallel, by a proper arrangement of switches, the battery can be discharged in series, and the full potential utilized. After charging, the voltage of each cell will fall to a little over 2 volts on open circuit, and on closed circuit will fall very nearly to 2 volts. As discharge takes place the specific gravity of the solution will fall and on a lower limit the battery should be recharged.

If a 220-volt circuit was available, the battery could be charged in series, and would require $\frac{220 - 125}{10} = 8.5$ ohms in the line.

In practice the actual resistance is not known, but a rheostat is used and adjusted from time to time so as to maintain the desired current reading in an ammeter placed in circuit.

Boosters.—If the source of voltage is not sufficiently high to overcome the counter E. M. F. of the battery and it is not desired to charge in parallel, other means must be used to help the charging voltage, and machines for doing this are called **boosters.**

An ordinary form of booster for this purpose consists of a shunt generator with its voltage regulated by its field regulator. This may be run by any means available, preferably by a motor, and so arranged in the circuit of the charging source as to add its voltage to that of the charging current. By varying the field of this booster generator, the charging current can be kept approximately constant.

Faults and Remedies.

Nearly all the troubles of storage batteries may be traced either to buckling of plates or bad forms of sulphating, and these are due to want of care either in charging or discharging. Cells that are to remain for a long time without use should be thoroughly charged, and from time to time, be recharged to keep them to the full voltage. This is to prevent the plates from sulphating due to local action and slow leakage due to bad insulation. The color of the plates will at once indicate sulphating as the positive plates instead of being a dark chocolate color will turn grayish all over or in patches, and if there is not a marked difference in the color of the positive and negative plates, something is wrong. Sulphating causes scaling of the plates, falling of the paste, and consequent buckling and short circuiting.

Bad insulation is a frequent source of leaks, and the shelves on which the cells rest should be kept perfectly dry and the glass cells should rest on wooden bases supported by insulators.

If sulphating has occurred, the white patches should be removed or else the paste is apt to fall out and they should be scraped off and if very bad the sections should be lifted from the cells, taken apart and thoroughly cleaned, and the cell itself cleaned of any deposit that may have fallen in it. Before removing a section, the electrolyte should be drawn off to prevent any danger of short circuits.

Buckling may arise from too high a charging or discharging rate and often arises from loose paste sticking between plates causing unequal resistance and unequal expansion and contraction. Sometimes plugs of paste fall out and this can happen without being noticed, though it usually follows a sudden large discharge.

The plates should never touch the bottom of the cells. A slight quantity of powder is usually found at the bottom, due to the white sulphate formed on the first charging.

In charging the greatest care must be observed to see that the leads of the charging circuit are properly connected, and the polarity should always be noted before charging commences. If connections are wrong, the plates throughout the battery become reversed, and the negatives become brown and the positives slate color. There is only one remedy for such a fault, and the cells must be discharged through a resistance but not so that the maximum discharge is exceeded. When the battery shows no E. M. F. or a very low value the leads can be joined up correctly and the charging current started very slowly at first, as there is now very little counter E. M. F. till the cells are charged up the right way. In doing this it is well to vary the current by an adjustable resistance and gradually allow the current to increase.

When the plates are sulphated, the internal resistance is greater and consequently the E. M. F. is much lower. In charging, if all plates are in good condition, they should be charged until there is free bubbling of gases, but if the capacity of the cell has been reduced by sulphating, the bubbling will occur too soon. This arises from the charging current being too great, as much of the counter E. M. F. has been removed. If bubbling does not occur at all, the paste may have fallen from the plates.

If a cell gives no E. M. F. from any cause except complete short circuit, the discharging current has the effect of charging the cell the wrong way. In discharging such a cell it should be disconnected, and connected when charging and in time it may regain its original E. M. F.

The Cadmium Tester.

When a lead cell is discharged to the point that the voltage between plates is about 1.8 volts, it should be considered as fully discharged. This voltage is the difference of potential between the plates, and depends on the state of charge on both plates. Similarly when fully charged the voltage between plates should be about 2.5 volts. If one is fully charged and the other but imperfectly charged, the capacity of the cell is affected. Both plates should be fully charged, and while the difference of potential between them may be obtained by a voltmeter, this will not suffice to determine whether both are fully charged. To determine the state of charge on each plate, recourse is had to the cadmium tester. This consists of a stick of pure cadmium, which should be free from impurities and should never be scraped bright. It is well to have it protected by a hard rubber tube perforated with holes for the circulation of the liquid.

At the end of charge a voltmeter connected to the positive plate, lead peroxide, and the cadmium, should show about 2.4 volts, and should show about .1 volt when connected to the negative plate, lead, and cadmium. The voltage between the two plates is the sum of the two readings, or $2.4 + .1$ volt $= 2.5$ volts. The cadmium is positive to the positive plate and negative to the negative, or the difference of potential between plates is $2.4 - (-.1) = 2.5$ volts.

At the end of discharge, the difference of potential between cadmium and the positive plate is about 2 volts and that between cadmium and the negative plate is about .2 volt. In this case cadmium is positive to both plates and the difference of potential between plates is $2.0 - .2 = 1.8$ volts.

Edison Storage Battery.*

The elements of a unit of the Edison storage battery consist of compounds of iron and nickel, and are placed in an alkaline solution contained in a can of sheet metal. The battery is manufactured in two principal types, known as A and B, each type being

* From the Edison Storage Battery. Compiled by J. B. Howell, Ensign, U. S. Navy.

made in several sizes. Type A is used when large current capacity is desired, and Type B on work which only calls for light current.

The following description refers to Type A-4, the numeral signifying the number of positive plates per cell, and in this type there are five negative plates. The positive plate is the anode when connected for charging and becomes the kathode on discharge. The positive pole for both operations is on the positive plate.

The **negative**, or **iron oxide plate**, comprises twenty-four rectangular pockets supported in three horizontal rows in a nickel-plated grid. These pockets are made of thin nickel-plated steel perforated with fine holes, and each pocket is filled with iron oxide. The whole is subjected to great pressure so that the active material becomes an integral part of the supporting grid.

The **positive** or **nickel oxide plate** consists of two rows of round rods or tubes, thirty in number, held in a vertical position by a steel supporting frame. These rods or tubes are made of nickel-plated perforated steel and are loaded with the active nickel material. They are put together with double-lapped spiral seams and reinforced with eight steel springs, which renders expansion impossible and insures perfect contact at all times.

In a cell the positive and negative plates are assembled alternately, all the positive plates being connected to the positive pole and the negative plates to the negative pole. The plates of each group are hung on a connecting rod on which they are correctly distanced by nickel-plated steel spacing washers and held firmly in contact by nuts screwed on both ends.

The retaining can is made of sheet steel, nickel plated, the walls of which are corrugated so as to give the greatest amount of strength with a minimum weight. This can is electroplated with nickel which protects it from rust and in addition gives it an attractive and finished appearance.

The **electrolyte** in which the plates are immersed consists of a 21% solution of caustic potash, KOH, which contains a small amount of lithium. The normal specific gravity of a 21% solution of KOH is 1.200 and this does not change during charge and discharge.

Chemical Reactions.—There are no complicated chemical changes within the cell. The positive active material is nickel hydrate and

the negative active material is iron oxide. On the first charge the nickel goes to an oxide in which the nickel has a higher valency and never reduces to its original state on future cycles. On every cycle the negative plate changes to metallic iron on charge and iron oxide on discharge.

On first charge the nickel hydroxide is converted to a high oxide, probably NiO_2, and the iron oxide or hydroxide is reduced to metallic iron.

On discharge the nickel oxide, NiO_2 of the positive is reduced to Ni_3O_4, and the iron of the negative is converted to Fe_3O_4. Upon recharging the products NiO_2 and Fe are again formed.

The electrolyte, potassium hydroxide, enters into the reaction, but in the end is regenerated and is undiminished in quantity. It is probably separated into the ions K and OH, which produce chemical change, after which the potassium hydroxide is again formed.

The chemical reactions for the above changes have been written as follows:

$$nKOH = nK + nOH \text{ (ions).}$$

In first charge—

$$Fe_2O_3 + 6K + 3H_2O = 2Fe + 6KOH \text{ (negative);}$$
$$3Ni(OH)_2 + 6(OH) = 3NiO_2 + 6H_2O \text{ (positive).}$$

In discharge—

$$3Fe + 8(OH) = Fe_3O_4 + 4H_2O \text{ (negative);}$$
$$6NiO_2 + 8K + 4H_2O = 2Ni_3O_4 + 8KOH \text{ (positive).}$$

In recharging—

$$Fe_3O_4 + 8K + 4H_2O = 3Fe + 8KOH \text{ (negative);}$$
$$2Ni_3O_4 + 8(OH) = 6NiO_2 + 4H_2O.$$

Possibly a simpler way of representing the above changes is to consider that the current on charge in passing from the positive to the negative plate decomposes the KOH into the ions K and OH, K passing with the current and carrying a charge. On reaching the negative plate, the charge is given up to it, after which the atom of K unites with the water to form KOH and H is liberated, thus—

$$2H_2O + 2K = 2KOH + H_2.$$

The H liberated then acts on the negative plate to reduce it to metallic iron, thus—

$$Fe_2O_3 + 6H = 2Fe + 3H_2O \text{ (negative).}$$

The ion OH formed on charge passes to the positive plate and on reaching it gives up its charge to it, after which it unites with water to form H_2O and O is liberated, thus—

$$H_2O + 2HO = 2H_2O + O.$$

The O liberated then acts on the positive plate, thus—

$$Ni(OH)_2 + O = NiO_2 + H_2O \text{ (positive).}$$

On discharge, K goes to the positive plate, liberating H, which acts on it, thus—

$$6NiO_2 + 8H = 2Ni_3O_4 + 4H_2O \text{ (positive).}$$

HO goes to the negative plate and O is liberated, which acts on it, thus—

$$3Fe + 4O = Fe_3O_4 \text{ (negative).}$$

On subsequent charge, the H liberated at the negative plate acts on it, thus—

$$Fe_3O_4 + 8H = 3Fe + 4H_2O \text{ (negative).}$$

And the O liberated at the positive plate acts on it, thus—

$$2Ni_3O_4 + 4O = 6NiO_2 \text{ (positive).}$$

There are probably other reactions that take place, as in some cells mercury is used in connection with the iron plate for purpose of better contact, and a barium compound in connection with the nickel oxide plate either to promote chemical action or to reduce internal resistance.

Charging.

To maintain the normal current rate throughout the charge, the line voltage must average at least 1.85 times the number of cells in series. Thus to charge 60 cells in series would require 60×1.85 volts or 111 volts. If the line voltage be 2% or 3% lower than that required by calculation, there will be no material interference with charging, though the normal rate cannot be maintained near the end of charge. If the normal rate cannot be maintained, the charging

must continue for a longer period. When the state of full charge is reached the voltage assumes a constant value, and it is possible after some experience to determine when a battery is fully charged by careful observations of its voltage. The normal charging rate can be maintained throughout unless the heating becomes excessive.

Discharging.

The normal discharge rates are the same as the normal charge rates. The average discharge voltage working at the normal rate is 1.2 volts per cell and the discharge is complete when an average of one volt per cell is reached.

Temperatures.

The best results are obtained from a battery when the temperature is kept between 75° and 95° F. during charge. The temperature of the battery should not be allowed to go above 105° F. during charge or 115° F. during discharge, and the lower the temperature is kept within the prescribed limits during charging, the longer will be the life of the battery.

The battery compartment should always be kept open while the battery is charging, and all holes and openings in the battery compartment should be kept closed during cold weather. If the temperature falls below 50° F. either during charge or discharge, the output and efficiency will be temporarily impaired.

Output and Efficiency.

The capacity of the Edison battery increases for some time after it has been put in service. It will give its rated output on normal charge when new, and after working some time will give a greater output. The process of self-forming continues over a period of from one to three months of regular service, and is assisted by overcharges at intervals.

A valuable feature is that the battery always has a reserve capacity which can be utilized by extending the length of charge. In a fully formed battery charged for ten hours at the normal rate, the output may reach 30% more than the rated output. In using this,

the highest available capacity of a battery, charging current is wasted and efficiency is sacrificed. The wasted current tends to decompose the water which escapes as gas, and this evaporation must be made up by adding distilled water or rain water. The proper height of the solution is ½″ above the plate tops, and the solution should never be allowed to get below the tops of the plates.

The so-called efficiency, the percentage of the energy used in charging available on discharge, is about 60%.

Advantages.

The advantages of the Edison battery over the lead, sulphuric acid battery are classified below.

1. It is compact and light. It has nearly double the capacity of a lead battery of the same weight, and for the same watt hour output it is only about half the weight of the lead battery.

2. It can be left for an indefinite period in either a charged or discharged condition without the slightest deterioration.

3. It has none of the objectionable features of sulphating and can remain charged or discharged.

4. It can remain with a given charge for any length of time and retain at least 80% of that charge.

5. There is no acid, either in liquid or gaseous state, to attack metals.

6. If necessary it may be charged and discharged at very high rates without harm.

7. There is no disintegration of active material at any stage of its life.

8. There is no local action within the cell.

Cell Characteristics.

The following table gives cell characteristics, weights, dimensions, etc., of A type cells:

	A-4	A-6	A-8
Normal ampere hour output	150	225	300
Average discharge voltage per cell	1.2	1.2	1.2
Rate of charge, amperes for 7 hours	30	45	60
Normal rate of discharge, amperes	30	45	60
Weight in pounds per cell complete	13⅛	19⅛	25⅛

Cleaning.

The outside of the cans should be kept clean and dry. If dirt is allowed to accumulate between the cells, it is liable to become moist with water and potash and an electrolytic action will result, which in time may corrode the retaining cans. If these become corroded or rusted they should be coated on the sides and bottom with vaseline. For a thorough cleaning the cells should be taken out of the trays, washed off and dried. and the trays should be thoroughly dried before reassembling.

Cells for Submarines.

A special cell has been designed for battleship and submarine use. The positive plate is made up of $\frac{1}{8}''$ tubes to reduce the internal resistance and to give a greater discharge rate. The tubes are mounted on the "A" size grid and nine of these small grids are mounted on a larger grid, 3 wide and 3 high. The negative plate consists of a similar large grid with nine of the "A" size plates mounted thereon, 3 high and 3 wide. This particular cell has 17 large positive plates and 18 large negative plates and are all assembled in nickel-plated steel containing cans made up exactly in the same manner as the small cells. Each cell is a unit. The steel containing can is hermetically sealed, with the exception of the gas vent, and each cell is individually ventilated by a tube leading into an exhaust tank.

A battery of 102 such cells has a weight of 51,000 lbs., a rated ampere hour capacity at the one-hour rate of 3060 amperes, and at the three-hour rate of 3825 ampere hours; equivalent in watt hours output at the one-hour rate to 312 K. W. hours, and at the three-hour rate to 468 K. W. hours.

The battery can be charged or discharged in one hour.

CHAPTER VI.

OHM'S LAW AND ITS APPLICATION TO SIMPLE AND DIVIDED CIRCUITS.

Ohm's law may be stated as follows: **The current which flows in a circuit is directly proportional to the difference of potential between the ends of the circuit, and inversely proportional to the resistance of the circuit across which the difference of potential is measured.**

In symbols, the law is expressed thus:

$$C = \frac{E}{R}, \tag{1}$$

where $C =$ current in amperes,
$E =$ difference of potential in volts,
and $R =$ resistance in ohms.

From (1) also $E = CR$, which expression affords a convenient way of expressing the law; that *the difference, or fall of potential between two points is equal to the current flowing between the two points, multiplied by the resistance between the two points.*

Problems on Ohm's Law.

1. An arc lamp requires a current of 8 amperes at a difference of potential of 44 volts. What will be the value of an external resistance placed in series with the lamp to produce this voltage on a 100 volt main?

The fall of potential through resistance must be $100 - 44 = 56$ volts, and as 8 amperes flows through this resistance, the resistance must be

$$R = \frac{E}{C} = \frac{56}{8} = 7 \text{ ohms.}$$

2. An electric heater is connected by means of a cable to constant potential mains. When 4 amperes are flowing in the circuit the difference of potential across the heater is 98 volts, and when 6.5 amperes are flowing, it falls to 93 volts. Find the resistance of the cable.

If x = resistance of cable, $4x$ is the drop of potential in the cable and $98 + 4x$ = potential of the mains.

Similarly $93 + 6.5x$ = potential of the mains,

or $98 + 4x = 93 + 6.5x$,

or $x = 2$ ohms.

3. A number of 100 volt incandescent lamps are connected at the end of a pair of mains connected to a dynamo. If the resistance of each main is .37 ohm, and the current is 14.6 amperes, what voltage must the dynamo produce at its terminals?

Resistance of cables $= 2 \times .37 = .74$ ohm.
Drop in cables $= .74 \times 14.6 = 10.8$ volts.
Potential at dynamo $= 100 + 10.8 = 110.8$ volts.

4. The resistance of the filament of an incandescent lamp when cold is 220 ohms. If this value decreases 35% when hot, what current will a pressure of 110 volts send through the filament?

5. A resistance of 20 ohms, on being added to a certain circuit caused the current flowing to be reduced from 13 to 9 amperes. What was the original resistance of the circuit?

6. An ammeter connected in series with a standard resistance of .1 ohm indicates a current of 23 amperes. The difference of potential across the standard resistance is found to be 2.28 volts. Determine the error in the ammeter reading.

7. One end (A) of a wire ABC is connected to earth, the other end (C) is kept at a constant potential of 100 volts. If the resistance of the portion AB is 9.6 ohms and that of BC 2.4 ohms, what current will flow along the wire and what will be the potential at the point B?

Ans. $8\frac{1}{3}$ amperes.
80 volts.

8. A primary cell, E. M. F. 1.8 volts, and a secondary cell are connected up in opposition with a resistance of 400 ohms and the strength of the current is observed. On rearranging the cells to send currents in the same direction, it is found that the resistance has to be increased to 4000 ohms in order to reduce the current to its former value. Neglecting the resistance of the cells, find the E. M. F. of the secondary cell, and the current produced.

Ans. E. M. F. = 2.2 volts.
Current = .001 ampere.

Simple Circuits.

So far only the difference of potential between two points with the relation existing between that difference of potential and the current and resistance have been considered. The next step is to consider the total E. M. F. in a circuit and the relation between E. M. F. current and resistance.

In considering the total E. M. F. Ohm's law may be thus stated: **The current produced by a source of E. M. F. is dependent directly on the E. M. F. and inversely on the resistance.**

In symbols as before

$$C = \frac{E}{R}$$

where $E =$ total E. M. F.

This means that the total current flowing through every point in a simple circuit depends directly on the *total* E. M. F. and inversely on the *total* resistance in circuit. The fall of potential around the whole circuit is equal to the total E. M. F. or the difference or sum of the individual E. M. F's., and is also equal to the sum of all the differences of potential from one point to another continuously around the circuit.

By a **simple circuit** is meant one in which the current follows but one path both in its internal and external parts. In other words, it is a circuit in which everything that goes to make up the circuit is in series with each other. The circuit may be made up of cells, leading wires, instruments of different kinds or any electrical apparatus, provided that everything is connected so that the same current traverses every portion of the circuit.

Fig. 13 represents a typical simple circuit; the battery B composed of four cells in series, an instrument G, a resistance R_1, and an electrolytic cell C_1, all in series. The same current will traverse every part of this circuit including the connecting wires 1-2, 3-4, etc.

If E represents the total E. M. F. of the four cells and C the current, r' the resistance of all the connecting and leading wires, and r the total internal battery resistance, then

$$C = \frac{E}{r + r' + G + R_1 + C_1}, \qquad \text{(a)}$$

G, R_1, and C_1 representing the resistances of the parts so lettered.

The fall of potential from 1 to 2 $= C \times$ resistance of $1 - 2$
" " " " 3 to 4 $= C \times$ " " $3 - 4$, etc.
" " " through $C_1 = C \times C_1$
" " " " $R_1 = C \times R_1$
" " " " $G = C \times G$
" " " " the battery $= C \times r$.

The fall of potential all around the circuit from 1 around again to 1 is,

$$Cr' + CC_1 + CR_1 + CG + Cr,$$

and this must equal E, the total E. M. F. of the battery; this corresponding to equation (a).

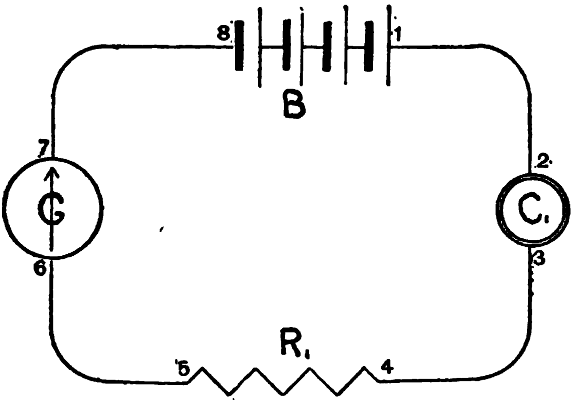


FIG. 13.—Simple Typical Circuit.

Problems as Applied to Simple Circuits.

1. A circuit consists of a dynamo of .5 ohm resistance and four separate resistances of 2, 6, 20, and 1.5 ohms respectively. If the total E. M. F. of the dynamo is 120 volts, find the value of the current flowing and the drop or fall of potential in each resistance.

$$C = \frac{E}{R} = \frac{120}{.5 + 2 + 6 + 20 + 1.5} = 4 \text{ amperes.}$$

Drop in separate parts =

$$\begin{aligned} 4 \times 2 &= 8 \text{ volts.} \\ 4 \times 6 &= 24 \text{ "} \\ 4 \times 20 &= 80 \text{ "} \\ 4 \times 1.5 &= 6 \text{ "} \\ 4 \times .5 &= 2 \text{ "} \end{aligned}$$

$$\text{Total drop} = \text{total } E = 120 \text{ volts.}$$

2. A battery produces a difference of potential at its terminals of 1.8 volts when sending a current of 2.2 amperes through an external resistance. Assuming the internal resistance of the battery to be .74 ohm, what is the total E. M. F. of the battery?

The fall of potential through battery, or lost volts

$$2.2 \times .74 = 1.63 \text{ volts.}$$

$$\text{Total E. M. F.} = 1.8 + 1.63 = 3.43 \text{ volts.}$$

3. A battery of 20 similar secondary cells sends a current of 6 amperes through the coils of an electromagnet having a resistance of 4 ohms. Determine the internal resistance of each cell, assuming each to have an E. M. F. of 2 volts.

$$C = \frac{E}{R} = \frac{40}{r' + 4} = 6$$

$$6r' = 16 \quad r' = 2.7$$

$$r' \text{ each} = \frac{2.7}{20} = .135 \text{ ohm},$$

or the drop in potential through electromagnet $= 6 \times 4 = 24$ volts.
$\therefore$ drop in battery $= 40 - 24 = 16$ volts,

or $$r' = \frac{16}{6} = 2.7.$$

Counter E. M. F. in a Circuit.—If there are one or more sources of E. M. F. in a circuit, the total is either the sum or the difference of the individual E. M. F's. Where one E. M. F. acts against the source of supply it is said to be a counter E. M. F. and one of the best examples of this counter E. M. F. in a circuit is that of a battery of secondary cells being charged from a dynamo. The E. M. F. of the battery acts against the E. M. F. of the dynamo, and current will only flow from the dynamo if its E. M. F. is the greater. Having found the E. M. F. required to exactly balance the counter E. M. F. of a battery, the additional E. M. F. required to send a charging current through the battery may be found by multiplying the total resistance of the battery by the current required.

Problems on Counter E. M. F.

1. A battery of 50 secondary cells is to be charged from a 125-volt mains, the current not to exceed 15 amperes. Assuming each cell to have an E. M. F. of 1.8 volts and an internal resistance of .004 ohm; determine the value of a resistance that will have to be put in series to accomplish the desired result.

Counter E. M. F. of battery	$= 50 \times 1.8$	$= 90$ volts.
Total internal resist.	$= 50 \times .004$	$= .2$ ohm.
Additional E. M. F. to force 15 amperes through battery	$= 15 \times .2$	$= 3$ volts.
Total E. M. F. required at terminals	$= 90 + 3$	$= 93$ volts.
Drop of potential in resistance	$= 125 - 93$	$= 32$ volts.
$\therefore$ resistance $= \frac{32}{15}$		$= 2.13$ ohms.

2. Two cells of E. M. F. 1.8 volts and 1.08 respectively are placed in a certain circuit in opposition. The current is found to be .4 ampere. What current will be produced if the cells are properly placed in series.

$$C = \frac{E}{R} \text{ or } .4 = \frac{1.8 - 1.08}{R}$$

$$R = 1.8 \qquad C' = \frac{1.8 + 1.08}{1.8} = 1.6 \text{ amperes.}$$

3. A battery of 50 storage cells is connected up with 5 connected the wrong way. Assuming the E. M. F. and internal resistance of each cell to be respectively 2 volts and .02 ohm, determine what voltage lamps in circuit would get (1) with the faulty connection (2) if they were connected up properly. Resistance of leading wires to lamps .2 ohm and of the lamps 4 ohms. *Ans.* (1) 68.9 volts.
(2) 76.9 volts.

Divided Circuits.

By a **divided circuit** is meant one in which the current does not follow one continuous path from the source of E. M. F., to its return, but rather two or more paths either in its external or internal parts, or both.

In order that the currents in the separate branches that go to make up a divided circuit may be calculated, it is necessary to know the resistances of the separate continuous branches that make up the whole circuit, and it is important to know what the joint resistance of two or more branch circuits may be.

Joint Resistance and Conductivity.

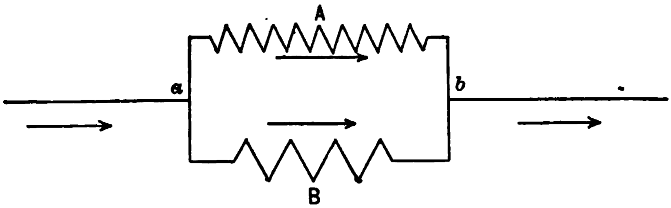


FIG. 14.—Resistance in Parallel.

If A and B, Fig. 14, are two conductors joined at a and b, it is required to know the joint resistance, or total resistance of A and B. These two conductors offer two paths for the flow of current, so the sum of the currents in A and B must equal the total current flowing from a towards b.

Conductivity represents the conducting property of conductors, and the joint conductivity from a to b, is the sum of the conductivities of A and B. The greater the conducting power of a conductor, the less the resistance must be; or, in other words, the resistance is the reciprocal of the conductivity.

Let

$$\begin{aligned} C_A &= \text{current in branch } A, \\ C_B &= \text{" " " } B, \\ R_A &= \text{resistance of branch } A, \\ R_B &= \text{" " " } B. \end{aligned}$$

Then the conductivity of A and $B = \frac{1}{R_A} + \frac{1}{R_B} = \frac{R_A + R_B}{R_A R_B}$

and, therefore, the joint resistance of A and $B = \frac{1}{\frac{R_A + R_B}{R_A R_B}}$,

or
$$\frac{R_A R_B}{R_A + R_B}.$$

If there was a third branch C, with resistance R_C the joint resistance would be $\frac{1}{\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}} = \frac{R_A R_B R_C}{R_A R_B + R_A R_C + R_B R_C}$.

If e is the difference of potential between a and b, by Ohm's law

$$e = C_A R_A = C_B R_B,$$

or

$$C_A : C_B :: R_B : R_A,$$

and

$$C_A + C_B : C_A :: R_A + R_B : R_B,$$

or

$$C_A = \frac{R_B}{R_A + R_B} C, \text{ where } C = C_A + C_B$$

and similarly $C_B = \frac{R_A}{R_A + R_B} C$.

By substituting in C_A its value from $e = C_A R_A$ it follows that

$$\frac{e}{R_A} = \frac{R_B}{R_A + R_B} C,$$

or

$$e = \frac{R_A R_B}{R_A + R_B} C.$$

This shows that the fall of potential e from a to b is equal first, to the current in one branch multiplied by the resistance of that branch, and the same for the other branch, and it is also equal to the total current in both branches C, multiplied by the total resistance of both branches, $\frac{R_A R_B}{R_A + R_B}$.

Laws of Divided Circuits—Kirchoff's Laws.

A consideration of the above facts leads to two laws by which all problems connected with divided circuits may be solved.

a. The algebraic sum of all the currents meeting in a point is zero, that is, the sum of all the currents flowing towards a point is equal to the sum of all those flowing away from it.

b. The total E. M. F. or fall of potential around any one closed circuit is equal to the sum of the products of the current from one point to another by the resistance of the conductor between the same points taken consecutively around the circuit.

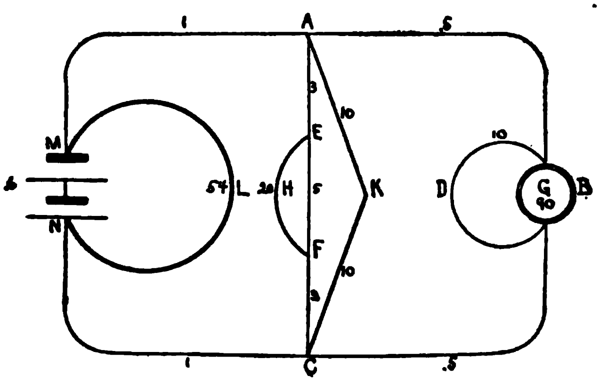


FIG. 15.—Illustration of Divided Circuits.

The application of divided circuits finds continual use in the practical arranging of batteries and outside circuits for firing primers, torpedoes, and defense mines, and also in calculations for determining the different efficiencies of dynamos and motors, all of which will be explained later by practical examples.

Illustration of Divided Circuits.

As an illustration of the method used in solving problems involving divided circuits, the following is given:

Given a divided circuit as shown in Fig. 15, the resistances being marked on the several branches. Given the current in the branch *ABC* as .72 ampere, find the total battery current and the total E. M. F. of the battery.

Joint resistance of G and $D = \frac{90 \times 10}{90 + 10} = 9.$

Resistance of $ABC = 9 + .5 + .5 = 10$

" " EF and $H = \frac{5 \times 20}{5 + 20} = 4$

" " $AEFC = 4 + 3 + 3 = 10$

" " $AEFC$ and K and ABC

$$= \frac{10 \times 20 \times 10}{10 \times 20 + 10 \times 10 + 20 \times 10} = 4$$

" " $MABCN = 4 + 1 + 1 = 6$

" " $MABCN$ and $L = \frac{6 \times 54}{6 + 54} = 5.4.$

Total resistance in circuit $= 5.4 + .6 = 6.$

Difference of potential between AC = current in $ABC \times$ res. ABC $= .72 \times 10 = 7.2$

Current in $AEFC$ = difference of potential between AC $\div$ resistance $AEFC = \frac{7.2}{10} = .72$

Current in AKC = difference of potential between $AC \div$ resistance $AKC = \frac{7.2}{20} = .36.$

Total current flowing in MA and $NC = .72 + .72 + .36 = 1.8.$

Difference of potential between M and N = current in $MABCN \times$ resistance $MABCN = 1.8 \times 6 = 10.8$

Current in L = difference of potential between M and $N \div$ resistance $L = \frac{10.8}{54} = .2.$

Total current flowing in battery = current in $MABCN$ + current in $L = 1.8 + .2 = 2$ amperes.

Total difference of potential or E. M. F. = total current $\times$ total resistance $= 2 \times 6 = 12$ volts.

Shunts and Compensating Resistances.

In making certain electrical measurements it is necessary that either all or a fraction of the current in the circuit be conducted through the measuring instruments. If currents are large, it is frequently not feasible to allow all the current to pass through the instruments, partly on account of the mechanical objections but generally on account of the delicate construction of the instruments which would be ruined by excessive current. In such cases, it is usual to employ a resistance called a **shunt**, which is placed in parallel with the instrument, and of such a resistance that most of the current will pass through it and only a small fraction through the instrument.

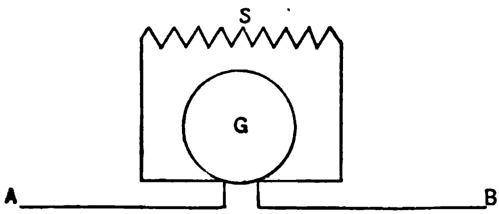


FIG. 16.—Illustrating Use of Shunts.

In Fig. 16 is represented an instrument G in series with an electrical circuit AB and shunted by the resistance S, called the **shunt.**

This is a case of divided circuits, in which the current in AB *divides*, part flowing through G and part through S.

If
$$C = \text{the total current}$$
$$C_G = \text{current through } G$$
$$C_S = \text{“} \quad \text{“} \quad S,$$
then
$$C = C_G + C_S.$$
If
$$G = \text{resistance of the instrument}$$
$$S = \text{“} \quad \text{“} \quad \text{shunt},$$
then by the first application of Ohm's law
$$C_G G = C_S S,$$
and
$$\therefore C = \left(\frac{G}{S} + 1\right) C_G. \tag{1}$$

The factor $\left(\frac{G}{S}+1\right)$ is called the **multiplier**, being the factor by which the current in G must be multiplied in order to find the total current.

To find the currents in G and S, we have from (1)

$$C_G=\left(\frac{S}{G+S}\right)C,$$

and it can similarly be shown that

$$C_S=\left(\frac{G}{G+S}\right)C.$$

Compensating Resistances.—The addition of a shunt to reduce the current flowing through an instrument results in making two paths for the current to flow and consequently the resistance is decreased and the current increased over its original value. In order to reduce the current to the original value, resistances, called **compensating resistances**, are placed in series with the current.

Problems on Shunts and Compensating Resistances.

1. A galvanometer having a resistance of 18 ohms is shunted by a resistance of 2 ohms. Calculate the value of the multiplying power of the shunt, and the compensating resistance.

$$M=\frac{G}{S}+1=\frac{18}{2}+1=10.$$

The original current $C'=\frac{E}{18}$ and $C=\frac{E}{\frac{36}{20}}$.

To reduce C to C' an additional resistance r must be introduced such that

$$C'=\frac{E}{r+\frac{36}{20}},$$

or

$$18=r+\frac{36}{20} \text{ or } r=16.2 \text{ ohms.}$$

2. A certain galvanometer of 4 ohms resistance requires a current of .01 ampere to produce a full scale deflection. Calculate the resistance of a shunt which, when used in conjunction with the galvanometer, will give a full scale deflection for 100 amperes. What resistance must be inserted in series with the galvanometer in order that a full scale deflection may be obtained for 100 volts.

$$C=\left(\frac{G}{S}+1\right)C_G$$

$$100=\left(\frac{4}{S}+1\right).01 \qquad S=.0004 \text{ ohm.}$$

If the fall of potential through galvanometer is to be 100 volts and current .01 ampere, the resistance is

$$R = \frac{E}{C} = \frac{100}{.01} = 10000,$$

or $10000 - 4 = 9996$ ohms must be added.

3. A millivolt-meter with 100 scale divisions has a resistance of 1.5 ohms. Calculate the resistance to be put in series with the instrument in order that the full scale deflection shall represent 100 volts; also calculate the resistance of a shunt in order that the full scale deflection shall represent 10 amperes.

One hundred scale divisions will represent $100 \times \frac{1}{1000} = \frac{1}{10}$ volt or with this voltage and resistance 1.5 ohms, the current through voltmeter is

$$C_G = \frac{\frac{1}{10}}{1.5} = \frac{1}{15} \text{ ampere.}$$

To represent 100 volts at the terminals, the total resistance must be

$$R = \frac{E}{C} = \frac{100}{\frac{1}{15}} = 1500 \text{ ohms}$$

and the added resistance $1500 - 1.5 = 1498.5$ ohms.

$$C = \left(\frac{G}{S} + 1\right) C_G \quad \text{or } 10 = \left(\frac{1.5}{S} + 1\right)\frac{1}{15}.$$

$\therefore \quad S = .01007$ ohm.

4. When measuring the value of a certain resistance, the volt-meter was connected up so as to measure the voltage, not only across the resistance, but also across the ammeter. The resistance of the voltmeter was 200 ohms, and of the ammeter .005 ohm. The ammeter reading was 25 amperes, and the volt-meter reading was 4.8 volts. Calculate the true value of the resistance. *Ans.* .187 ohm.

Problems as Applied to Divided Circuits.

1. Two torpedo circuits (figure 17) *A* and *B*, are connected to a battery of E. M. F. of 17.5 volts and a total resistance of 3 ohms. The leading wires *C*, *D*, *A*, and *B* have a resistance of 1 ohm each. In *A* are 4 fuses in series. How many in series in *B* can be inserted, so that all will ignite simultaneously? Each fuse has a resistance of .5 ohm and requires .5 ampere to ignite it.

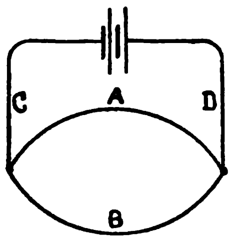


FIG. 17.

To insure ignition it must be assumed that .5 ampere flows in *B*, for *A*'s resistance being less, there will be more than .5 ampere in that

branch, and how much more flows in that branch is a matter of indifference, as if each branch has .5 ampere or over, the fuses will all ignite together.

$$x = \text{No. of fuses required,}$$
$$C = \text{Current in battery,}$$
$$C_A = \text{" " branch } A,$$
$$C_B = \text{" " " } B,$$

then $17.5 = 3 \times C + C \times 1 + (4 \times .5 + 1)\ C_A + C \times 1,$

$$17.5 = 3 \times C + C \times 1 + (x \times .5 + 1)\ .5 + C \times 1,$$

$$C = C_A + C_B \qquad C_A + .5 = C$$

$$17.5 = 5C_A + 2.5 + 3C_A \qquad \text{or } C_A = \frac{15}{8}$$

$$3C_A = (.5x + 1)\ .5, \qquad \text{or } x = 4 \times \frac{41}{8} = 20.$$

2. A battery (figure 18) of 15 volts E. M. F. and 6 ohms resistance has its poles connected by three circuits in multiple arc. Two of these contain fuses and their resistances with the fuses are 2 and 3 ohms respectively. What is the greatest resistance that can be given the third circuit without igniting the fuses, if ½ ampere be required to ignite a fuse?

The current of ½ ampere must be in the circuit of smallest resistance. Solve as preceding problem. *Ans.* $x = ⅔$ ohm.

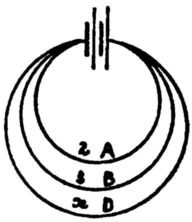


FIG. 18.

3. With a constant E. M. F. of 5 volts at E (figure 19), what is the current through h, a, b, and c, the resistance of the parts FhG, FaG, FbG, and FcG being 8, 4, 3, and 6 ohms respectively?

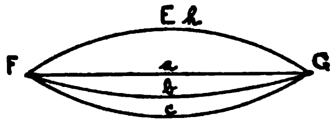


FIG. 19.

$$5 = 8C_h + 4C_a,$$
$$4C_a = 3C_b = 6C_c,$$
$$C_h = C_a + C_b + C_c,$$

or $\quad 5 = 8C_a + \dfrac{8 \times 4C_a}{3} + \dfrac{8 \times 4C_a}{6} + 4C_a \qquad$ or $C_a = .1785$ amp.

$$C_b = \frac{4}{3}\,C_a = .238 \qquad C_c = \frac{4}{6} \times C_a = .119,$$

$$C_h = .1785 + .238 + .119 = .5355,$$

or the total external resistance $= \dfrac{1}{¼ + ⅓ + ⅙} = \dfrac{12}{9}$

$$C_h = \frac{5}{8 + \frac{12}{9}} = \frac{45}{84} = .5356 \text{ as before.}$$

4. A battery of 4 cells is arranged as in the diagram (figure 20). Required, the current through the battery and the wire E, and the difference of potential between B and C. The E. M. F. of each cell is

1.8 volts, resistance of each cell .5 ohm, resistance of $AB = 2$ ohms, of $CD = 3$ ohms, $E = 4$ ohms, $F = 6$ ohms, $G = 7$ ohms.

If the wire G were cut, would the current through the battery be increased or decreased; would it be increased or decreased through E?

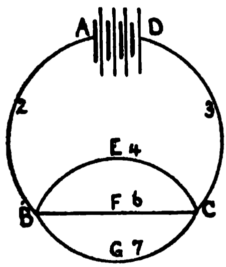


FIG. 20.

Total $R = 4 \times .5 + 2 + 3,$

$$+ \frac{4 \times 6 \times 7}{4 \times 6 + 4 \times 7 + 6 \times 7}$$

$$C = \frac{E}{R} = \frac{4 \times 1.8}{R}$$

$= .819$ ampere through battery,

$4C_E = E - 2C - 2C - 3C,$

$= 7.2 - 5.733 = 1.467,$

$$C_E = \frac{1.467}{4} = .366.$$

If G were cut, the resistance would be increased, and the battery current would be decreased.

Difference of potential between B and $C = 4C_E = 1.467.$

$4C_E = E - 7C.$ Now if C is decreased, $4C_E$ is increased and that being the difference of potential between B and C the current through E would be increased.

5. The interpolar portion of a voltaic circuit consists of three separate wires in multiple arc, their resistances being 30, 50, and 70 ohms. If the E. M. F. of the battery is 5 volts and internal resistance 6 ohms, find the current in battery and through wire of greatest resistance.

Ans. Battery current .24 ampere.
Current through greatest resistance .0508 ampere.

6. Suppose a battery and wires connected as in the diagram, figure 21.

Resistance of $ADB = 50$ ohms, $ACB = 30$ ohms and EB an unknown resistance. A volt-meter connected at E and B shows the same reading as when connected at A and C. The resistance of AC being ⅓ of ACB, find the resistance of EB.

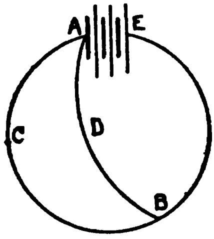


FIG. 21.

$$e_{A.C} = \frac{30}{3} \times C_{A.C} = x \times C_{EB}$$

$x =$ unknown resistance

$$50 \times C_{AB} = 30 \times C_{AC} \qquad C = C_{AB} + C_{AC}$$

$$C_{AB} = \frac{3}{5} C_{AC}.$$

$$\therefore \quad C_{EB} = \frac{3}{5} C_{AC} + C_{AC} = \frac{8}{5} C_{AC}$$

$$\frac{10 \times C_{AC}}{C_{EB}} = x,$$

$$\text{or} \qquad x = \frac{10 \times C_{AC}}{\frac{8}{5} \times C_{AC}} = 6.25 \text{ ohms.}$$

7. Three parallel circuits contain 14, 10, and 4 torpedoes respectively and resistance of leading wires in each circuit is 1 ohm. What is the smallest number of cells (E. M. F. of each 1 volt and internal resistance of each .6 ohm) required to explode all the torpedoes simultaneously and how must the cells be arranged? Resistance of each fuse .5 ohm and requires 1 ampere to fire it.

Assumption necessary: that the current in the greatest resistance must = 1 ampere. *Ans.* 96 cells required; 6 groups in parallel, and 16 cells in series in each group.

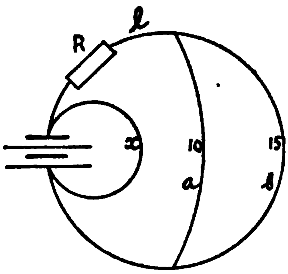


FIG. 22.

8. Taking problem 4 under grouping of cells, what resistance added to l will prevent the firing of the fuses? Find the greatest resistance which, used a shunt between the poles of the battery, will prevent firing (figure 22).

Solution of the problem mentioned shows that the battery should be composed of 36 cells, all in series.

If in a there is anything less than ¾ ampere, the fuses will not fire in that branch, and in b the resistance being greater than in a, they will not fire. If there is just ¾ ampere in a, we have $10C_a = 15C_b$, or $C_b = \frac{10}{15} \times \frac{3}{4} = \frac{1}{2}$ ampere, or the whole current must be $\frac{3}{4} + \frac{1}{2} = \frac{5}{4}$ ampere.

The problem now becomes, what resistance R added in series in the main circuit will make the battery current $= \frac{5}{4}$ ampere.

$$C \text{ total} = \frac{E \text{ total}}{R \text{ total}}, \qquad \text{or} \qquad \frac{36}{36 \times \frac{1}{4} + R + \text{ext. res.}} = \frac{5}{4};$$

$$\text{ext. resist.} = 3 + \frac{10 \times 15}{10 + 15} = 9 \text{ or } 5R = 36 \times 4 - 90,$$

$$R = 10.8 \text{ ohms.}$$

$\frac{5}{4}$ ampere must be the least current in the external (fuse) circuit in order that the fuses will not fire.

$$\text{Total external resistance} = \frac{9x}{9 + x},$$

or $$C \times \frac{9x}{9 + x} = 9 \times \text{fuse current or } C \text{ total} = \frac{5(9 + x)}{4x}$$

$$C \text{ total} = \frac{E \text{ total}}{R \text{ total}} = \frac{36}{9 + \frac{9x}{9 + x}} = \frac{5(9 + x)}{4x}.$$

or $$\frac{36 \times 4x \times (9 + x)}{81 + 18x} = 5(9 + x) \qquad x = 7.5 \text{ ohms.}$$

Illustration of Application of Kirchoff's Laws—Derivation of Formula for Comparing E. M. F. of Cells and for Finding Resistance of a Cell.

(See Chapter III.)

By Kirchoff's laws, Fig. 23,

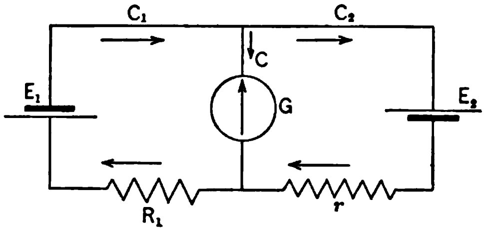


FIG. 23.—Connections for Comparing E. M. F. of Cells.

$$C_1 = C + C_2, \quad (1)$$
$$E_1 = C_1R_1 + CG, \quad (2)$$
$$E_2 = C_2r - CG, \quad (3)$$

substituting the value of C_1 in (1), in (2)

$$E_1 = CR_1 + C_2R_1 + CG,$$

from (3)

$$C_2 = \frac{CG + E_2}{r},$$

or

$$E_1r = CR_1r + CGR_1 + R_1E_2 + CGr$$

and

$$C = \frac{E_1r - E_2R_1}{R_1r + GR_1 + Gr};$$

when the balance is established $C = 0$, or

$$E_1r - E_2R_1 = 0,$$

or

$$\frac{E_1}{E_2} = \frac{R_1}{r}.$$

If the resistances of the batteries cannot be neglected, they must be added to R_1 and r, or

$$E_1(r + r'') = E_2(R_1 + r'). \quad (4)$$

By adding a resistance P to R_1 and Q to r, we have

$$E_1(r + r'' + Q) = E_2(R_1 + r' + P). \quad (5)$$

From (4) and (5) $E_1Q = E_2P,$

or

$$\frac{E_1}{E_2} = \frac{P}{Q},$$

or the E. M. F's. of the two batteries are directly proportional to the added resistances after balancing in R_1 and r. The service testing set can be used for the resistance R_1 and r, the balance arms being used for this purpose.

Derivation of Formula for Finding Resistance of Battery.

(See Chapter III.)

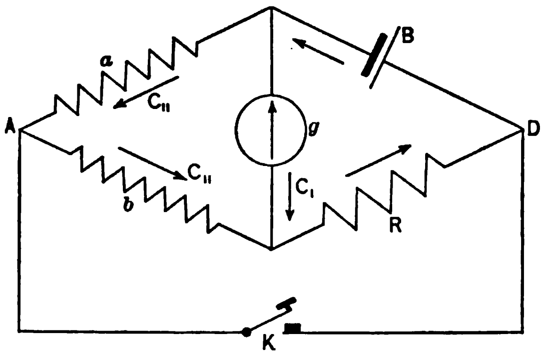


FIG. 24.—Connections for Determining Resistance of a Cell.

In Fig. 24 let E = E. M. F. of cell,
C = total battery current,
$C_{,}$ = current in g,
$C_{,,}$ = current in a and b.

When key is open, current flows through the joint resistances $(a + b)$ and g, the resistance of which is $\frac{(a+b)g}{a+b+g}$.

$$C = \frac{E}{R + B + \frac{(a+b)g}{a+b+g}}$$

$$C_{,}g = C_{,,}(a+b) \qquad C_{,} + C_{,,} = C$$

$$C_{,} + \frac{C_{,}g}{a+b} = C \quad \text{or} \quad C_{,}(a+b+g) = (a+b)C$$

or $$C_{,} = \frac{E}{R + B + \frac{(a+b)g}{a+b+g}} \times \frac{a+b}{a+b+g}.$$

This reduces to

$$C_{\prime} = \frac{E(a+b)}{(R+B)(a+b)+g(a+b+R+B)}\,. \qquad (1)$$

When the key is closed and A and D are at the same potential, current flows as though A and D were directly connected, current flowing in the divided circuit b and R in series with g, and the whole forming a divided circuit with a. This is shown in Fig. 25.

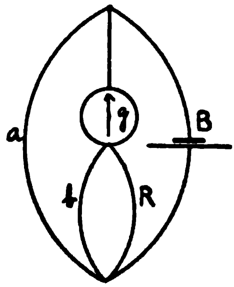


FIG. 25.

The resistance of b and R is $\dfrac{bR}{b+R}$.

The resistance of b, R, and g is $\dfrac{bR}{b+R}+g$.

The resistance of b, R, g, and a is $\dfrac{\left(\dfrac{bR}{b+R}+g\right)a}{\dfrac{bR}{b+R}+g+a}$.

$$C = \frac{E}{B+\dfrac{\left(\dfrac{bR}{b+R}+g\right)a}{\dfrac{bR}{b+R}+g+a}}$$

$$C_{\prime\prime}a = C_{\prime}\left(\frac{bR}{b+R}+g\right) \qquad C_{\prime}+C_{\prime\prime}=C$$

$$C_{\prime}+\frac{C_{\prime}\left(\dfrac{bR}{b+R}+g\right)}{a}=C$$

$$C_{\prime}\left(a+\frac{bR}{b+R}+g\right)=aC$$

$$C_{\prime} = \frac{E}{B+\dfrac{\left(\dfrac{bR}{b+R}+g\right)a}{\dfrac{bR}{b+R}+g+a}} \times \frac{a}{a+\dfrac{bR}{b+R}+g} \qquad (2)$$

When the current in the galvanometer is the same, the deflection is the same and equation (1) = (2).
or

$$\frac{(b+R)a}{BbR+Bbg+Bba+BRg+BRa+abR+abg+aRg} = \frac{a+b}{aR+aB+bR+bB+ga+gb+gR+gB}.$$

This reduces to

$$aR(aR+bR+gb+gR)=bB(aR+bR+gb+gR),$$

or

$$aR=bB,$$

or

$$B=\frac{aR}{b}.$$

CHAPTER VII.

MAGNETISM AND ELECTROMAGNETISM.

Magnetism.

Magnetism is the science that teaches of the properties of magnets. The name *magnet* was originally applied to a mineral known as *magnetite,* an oxide of iron of the chemical composition Fe_3O_4, which in its native state has the power of attracting iron. It has the power of imparting its magnetic properties to pieces of iron or steel brought near it, and such pieces of iron or steel are then said to be *magnetized* and are then called *magnets.* Iron or steel may be magnetized in other ways, the principal of which is by means of the electric current.

The Compass.—One of the most common examples of a magnetic substance is seen in the ordinary mariner's compass needle, a pivotted needle, highly magnetized, which, when at rest and undisturbed by local magnets, takes a position that indicates magnetic north and south. The end of the needle that points towards magnetic north is called the *north-seeking pole,* or briefly the **north pole** of the needle, and similarly the other end is called the **south pole** of the needle.

This needle acts under the influence of some force, inherent in the earth and in the space surrounding it which causes it to take a certain definite position. The region surrounding the earth and near it seems to be under the influence of this force or of varying forces, the origin of which lies in different points on the earth's surface. These points are called the **magnetic poles** of the earth, one representing the concentration of all the forces exhibiting one peculiarity, which may be called **positive,** and which is known as the **north magnetic pole** of the earth; another, the concentration of all the forces of opposite peculiarity which may be distinguished by being called **negative** and which is known as the **south magnetic pole** of the earth.

Recent investigations seem to indicate that there is only one north magnetic pole but one or more south magnetic poles. Emanating and radiating from these poles, there may be considered an indefinite number of lines, the direction of which at any place representing the direction of the resulting forces due to the opposite poles at that place. These imaginary lines may be considered as form-

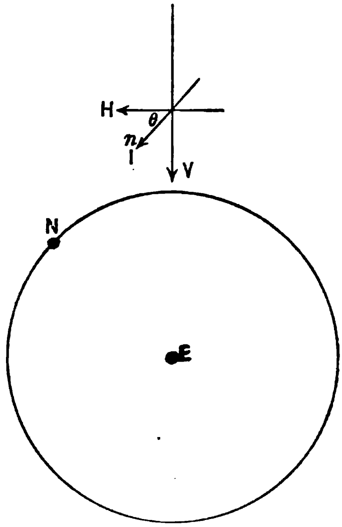


FIG. 26.—Illustrating Earth's Magnetic Force.

ing closed curves, running through the earth from the south to the north pole, and through the space surrounding the earth, from the north to the south pole.

At any place on the earth's surface, the direction of one of these imaginary lines would be that which a freely suspended magnetic needle would take.

In Fig. 26, let the circle E represent the cross-section of the earth and N the north magnetic pole. A freely suspended magnetic needle n, will turn so as to place itself in the direction of the magnetic lines at the place of suspension, and its north end will point towards the north magnetic pole, and it is urged towards the latter with a certain force called the **earth's total force,** designated by the letter I.

This force may be resolved into two forces, one parallel to the earth's surface, called H and the other vertical to the earth and called V.

If $\theta =$ the angle the needle makes with the horizontal

then $$H = I \cos \theta$$
$$V = I \sin \theta$$
and $$I = \sqrt{H^2 + V^2}.$$

As the point of suspension of the needle approaches the poles, the angle θ will increase, and when $\theta = 90°$

$$V = I \sin 90° = I.$$

At the pole then the horizontal force is zero, the vertical force is equal to the total force, and the needle points vertically up and down.

When θ becomes zero,

$$H = I \cos 0° = I,$$

and at that place, the needle is parallel to the earth's surface and there is no vertical force. The locus of all the places where the earth's vertical force is zero is called the **magnetic equator.**

The angle θ that the needle makes with the horizontal at any point on the earth's surface is called the **Dip.**

Magnetic Field.

All the space surrounding the earth and which is subject to the forces due to the poles is called the earth's magnetic field, and in general a magnetic field may be defined as **a space in which magnetic action takes place, or a region in which a magnet pole is acted on by a force tending to move it in one direction or another.** Magnetic fields may be produced by the earth, by magnets, by magnetic substances, by electromagnets, or by electric currents. The magnetic field of a magnetic substance is similar to that produced by the earth, and all magnets may be considered as small imitations of the earth, regarded as one huge magnet. For instance, an ordinary bar magnet has its poles and its magnetic equator or neutral line and its magnetic field surrounding it, represented by a number of lines forming curves through the magnet and the space surrounding it.

The poles of an ordinary bar magnet are close to the ends of the magnetic axis; they are of equal strength and opposite sign. In an indefinitely thin bar, uniformly magnetized, the poles are at the extremities of the magnet, and at these points the magnetic force is greatest.

In Fig. 27 is shown the magnetic field due to a bar magnet, in which the dotted lines represent the directions in which the forces due to the poles at N and S act, while the number of lines is a

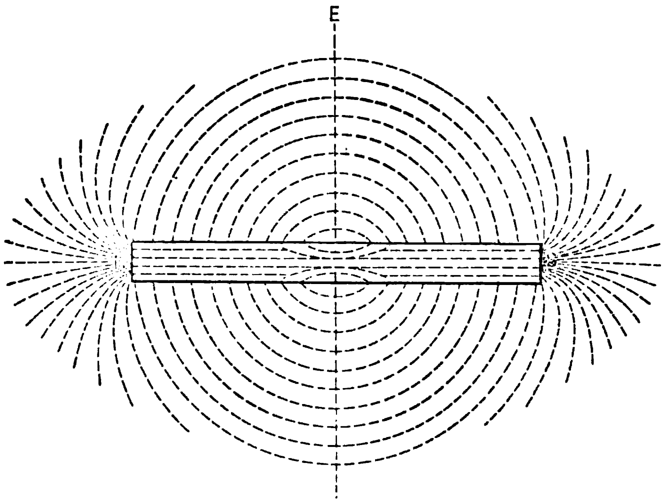


FIG. 27.—Magnetic Field Due to the Bar Magnet.

measure of the strength of the poles. All the lines pass through the central portion of the magnet, the *equator*, but begin to emerge from the sides of the magnet as the poles are approached on either side of the equator. Most of the lines pass through the interior of the magnet and emerge from the poles, and each line is continuous and completes its path in the region outside the magnet.

Free Magnetism.—Whenever the lines representing the magnetic field emanate from a magnetic substance and pass into the space surrounding it, the body is said to possess **free magnetism,** and any magnetic substance placed in this region will become magnetic and experience a force of attraction or repulsion.

Thus the magnetism of the bar magnet shown is all free and capable of producing magnetic induction.

Unit Magnetic Field.—A Unit Magnetic Field is defined to be one of such strength that it will act on a unit magnetic pole placed in the field with a force of one dyne.

A Unit Magnetic Pole is one of such strength that if placed in air one centimetre from a similar and equal pole, it will be repelled with a force of one dyne.

Thus, if it is said that the earth's horizontal component of its total force is .2 at any place, it is meant that at that place, a unit magnetic pole would be acted on with a force of .2 dyne.

The strength of a magnetic field may also be defined by the number of imaginary lines, portions of the closed curves, embraced in a given area at right angles to the direction of the lines. The intensity of the magnetic field at any point is represented by the number of these lines at that point, and a magnetic field has *unit intensity,* or a *unit magnetic field* exists when it *embraces one line, in air, per unit of area,* that is per square centimetre.

Laws of Magnetic Force.—

First Law.—Like magnetic poles repel one another; unlike magnetic poles attract one another.

Second Law.—The force exerted between two magnetic poles is proportional to the product of their strengths and is inversely proportional to the square of the distance between them.

Lines of Force Due to a Magnet Pole.—If the two magnetic poles are unit poles and are one centimetre apart, the force exerted between them is

$$f = \frac{mm'}{d^2} = \frac{1 \times 1}{1^2} = 1 \text{ dyne.}$$

From the definition of unit magnetic field, that a unit magnetic pole placed there is acted on by a force of one dyne, it follows that unit magnetic field must exist at unit distance from a unit pole. The surface of a sphere one centimetre in radius is equal to 4π square centimetres, and as unit field exists one centimetre from unit pole, or has one line of force per square centimetre, it follows that from every unit pole there must emanate 4π lines of force.

Magnetic Moment and Intensity of Magnetization.

If the strength of the poles of a magnet is m and the distance between them is l, the **moment of the magnet** is

$$M = m \times l.$$

The external effect of a magnet is the result of a certain condition of the metal which extends throughout the length of the bar, and any portion cut from the metal will exhibit the same magnetic qualities. If the magnetization of the whole magnet is uniform, the moment of every portion would be proportional to its volume.

The moment per unit of volume is called the **intensity of magnetization** and is denoted by I, or

$$I = \frac{ml}{V}$$

where $V =$ volume.

If the cross-section is uniform, the strength of pole is $m = Is$, as $V = ls$, where s is the area of cross-section.

Lines of Force and Induction.

Lines of force are defined as imaginary lines, which by their direction show the resultant of the magnetic forces acting at the point, and by their number, the magnitude of the force. The direction of the lines of force is that in which a free isolated magnetic pole would tend to move if placed in the field, the positive direction being that in which a positive pole would be repelled by a north pole or attracted by a south magnetic pole. These are supposed to exist in air, and the number of lines that are embraced in a unit area at right angles to the direction of the lines is a measure of the intensity of the field at that point. If the earth's horizontal force was given as .2, it would mean .2 of unit strength, or that every square centimetre embraced .2 of a line of force, but as this is impossible, it would have such a strength that would be represented by 20 lines of force per square decimetre.

The strength or intensity of the field is usually denoted by H, and is independent of the source which produces the field. H is measured by the force which a unit pole would experience if placed in that field. Thus, if a pole of strength m is placed in a field of strength H, it would be acted on by a force of

$$F = mH \text{ dynes.}$$

Besides the lines of force which pass into the air, there are other lines which are conceived as only passing through the metal of the magnetic substance; these lines representing the *intensity* of magnetization in the magnet. The strength of pole m being equal to Is, and each unit pole having 4π lines, the total number of lines of magnetization in the magnet itself, independent of the lines of force in air, is $4\pi Is$, or per unit of area, $4\pi I$.

The resultant of the lines of force and the lines of magnetization are called **Lines of Induction.**

Magnetic Induction.

Magnetic induction is the phenomenon of inducing magnetism in a magnetic substance by the *influence* of another magnet, and a magnetic material placed in a magnetic field becomes magnetic by the influence of the lines of induction described above.

Soft iron lying in the magnetic field of the earth becomes magnetic, and of greater or less strength, depending on its position relative to the lines of induction of the earth's magnetism. Thus, a long, straight bar lying parallel to the lines of force or in the magnetic meridian may become strongly magnetic, the part pointing to the north of opposite polarity to that of the north magnetic pole of the earth. In this position it embraces a great many lines of force. As the bar is turned from the meridian, the number of lines embraced continually diminishes and the resulting induction grows less, until the bar is east and west, when its ends show practically no magnetism. However, in this position, the whole half of the bar lying broadside to north will have magnetism opposite to that of the north magnetic pole and opposite to the other half.

If the bar is held vertical, it will have induced in it, however it may be turned in azimuth, magnetism due to the vertical component of the earth's total force, the lower end having magnetism opposite to the magnetic pole of the hemisphere in which the experiment is made.

Magnetic induction takes place in any magnetic substance which is near enough to allow the lines of force from the magnetizing substance to pass through it. North and south polarity is always set up, and the induced polarity can always be told, if the direction

of the inducing field is known, for no matter what the shape of the magnetic substance, a south pole will always be formed where the lines of force *enter* the substance and a north pole where they *leave* it. In other words, poles of the inducing substance induce opposite polarity to themselves, and the pole nearer to the inducing magnet will be of the opposite kind.

A substance magnetized by induction exhibits all the properties of a magnet while under the influence of induction, but generally loses most of them when the magnetizing substance is removed. If the number of lines passing through the material placed in a magnetic field is greater than the number of lines that previously passed through the same space in air, the material is said to be **paramagnetic,** and if less than before, **diamagnetic.** Thus, the iron bar lying in the magnetic meridian was paramagnetic; if the rod had been zinc, the number of lines passing through the zinc would have been less than through the same space in air, and it would have been diamagnetic.

Paramagnetic and Diamagnetic Substances.

A list of some of the principal paramagnetic and diamagnetic substances is given:

Paramagnetic.

Iron,	Nickel,	Cobalt,	Aluminum.

Diamagnetic.

Bismuth,	Air,	Silver,	Water,
Antimony,	Mercury,	Copper,	Alcohol.
Zinc,	Lead,	Gold,	

When a material is lying in a magnetic field the total number of lines passing through the material per square centimetre of cross-section at right angles to the lines is a measure of the magnetic induction and is usually denoted by B. This B consists of the $4\pi I$ lines mentioned above as representing the intensity of magnetization per unit area of cross-section and the H lines due to the magnetizing force, or $B = 4\pi I + H$.

Magnetic Permeability and Susceptibility.

Suppose a magnetic field of strength H, and a magnetic material placed in it experiences an induction B; or, in other words, there are B lines per unit of area in the material, while in the same space in the air there were but H lines, then the ratio $\frac{B}{H}$ is called the *permeability* of that material, usually denoted by μ, which is called the **coefficient of permeability.** Similarly, if the intensity of magnetization becomes I, the ratio $\frac{I}{H}$ is called the *susceptibility* of that material, denoted by k, called the **coefficient of susceptibility.**

$$\mu = \frac{B}{H} \text{ and } k = \frac{I}{H} \text{ and } B = 4\pi I + H,$$

whence it follows that $\mu = 4\pi k + 1$.

Electromagnetism.

Electromagnetism treats of the relation existing between electric currents and magnetic fields.

Magnetic Field Due to Current in a Straight Conductor.

If a straight conductor is held over and parallel to a small pivotted magnetic needle which is pointing towards magnetic north, and an electric current is passed through the conductor, the needle will be deflected one way or another out of the magnetic meridian. This experiment shows that there must have been some force brought into existence by the current in the conductor that was not present when the current did not flow.

This deflection of the magnetic needle is not due directly to the electric current, as the conductor does not touch the needle in any way, but it is due to a condition established by the current, the setting up of a magnetic field around the conductor, and it is the reaction of the two magnetic fields, that due to the magnet and that due to the current, which causes the needle to take a position dependent on the resultant of the two forces.

A straight conductor carrying a current has then set up around it a magnetic field which is dependent for its intensity and on the

distance its properties are manifested directly on the strength of the current. This magnetic field consists of a series of concentric curves, or rings, surrounding the conductor, the lines representing the field being in every way similar to the lines of force of magnetic substances. These lines have no absolute geometrical form, but rather are a mass of whirls or eddies surrounding the conductor. They are brought into existence by the current, and increase with the current and die out with it, seeming to collapse like rubber bands that have been stretched, when the current has faded to zero, and spreading out as the current is increased. An idea is given of their form and direction in Fig. 28.

In Fig. 28, the lines of force are drawn as concentric circles around the conductor, but as a matter of fact as stated above they

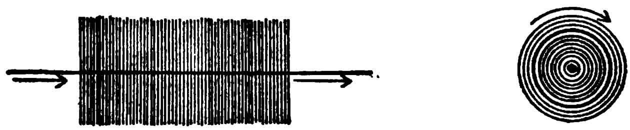


FIG. 28.—Magnetic Field due to Straight Current.

may or may not have a symmetrical form. In the right hand sketch, the central dot represents the conductor, with the current flowing away from the observer, in which case the positive direction of the lines of force is clockwise or right-handed and the heavy circle has been drawn to represent the resultant of all the lines of force due to the current. This field will remain of constant intensity as long as the current remains steady, but will change in strength as the current starts, stops, or changes its rate of flow.

Knowing now the character of the field set up around a conductor carrying a current and the field of the magnetic needle, it is easy to account for the deflection of the needle under the influence of a current of electricity.

The upper figure in Fig. 29 represents the cross-section of the conductor flowing away from the observer and marked *IN*, and the circle represents the resultant of the lines of force. Under the conductor and parallel to it is shown the cross-section of the needle,

the north end marked *N*. The positive direction of the magnetic whirls is clockwise, and these whirls apparently striking the north end of the needle, there is a reaction between the two magnetic fields, and both being positive, there is mutual repulsion, the field of the current being pushed out of its natural path, and the north end of the needle being repelled to the left. There is also attraction between the field of the current and the south pole of the needle, tending still more to deflect the north end of the needle to the left. If the needle were placed over the current, the north pole would be pushed to the right and opposite deflection would be the result.

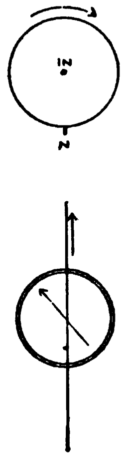


FIG. 29.

The resultant action of the two fields is also explained by the following general principle: **Whenever two different magnetic fields are near one another and capable of influencing one another, and one is fixed while the other is movable, the movable one will always tend to move to such a position that will cause the two fields to have one common path in one direction.**

In the above illustration, in order that the two fields may have one common path in one direction, the needle will have to turn at right angles to the conductor, when the magnetic lines due to the current would run through the needle from the south pole to the north, and from the north pole of the needle around the conductor in air to the south pole of the needle.

Rules for Remembering Direction of Field and Current.—The lower sketch shows the conductor over the needle and flowing up, the needle being deflected to the left. There are several rules for remembering the relation between the direction of the current and the directior of the deflection of the needle, one being the application of the word *snow,* illustrated in the above sketch. If the current is from south to north over the needle, the deflection of the north end of the needle is to the west, the initials of *south, north, over, west,* forming the word **snow.**

Conversely by knowing the direction of deflection, and the position of the needle in reference to the conductor, the direction of the current is at once known.

One of the simplest rules for remembering the direction of the lines of force due to a current is that known as the **Hand Rule.** *Grasp the conductor with the right hand with the thumb turned away from the hand and pointing in the direction in which the current is flowing. The direction in which the finger tips point is then the positive direction of the lines of force.*

Laws of Parallel Currents.

These laws may be stated here as they are so readily explained by a consideration of the magnetic fields surrounding conductors carrying currents, and illustrate so well the resultant action of those fields.

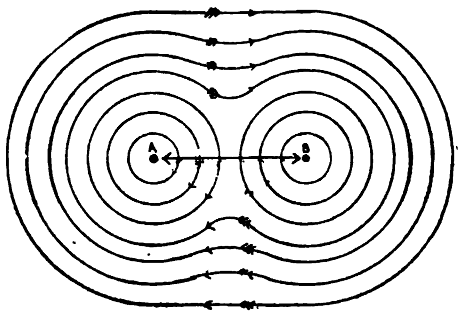


FIG. 30.—Magnetic Field of Parallel Conductors in Same Direction.

Parallel conductors carrying currents of electricity are mutually attracted if the current is flowing in each in the same direction, and are mutually repelled if the currents are flowing in opposite directions.

Fig. 30 shows two parallel conductors *A* and *B,* the current in each flowing away from the observer, and each surrounded by its own magnetic field, which is indicated by a few representative lines. The arrows show the positive direction of the lines of force, the same in both cases, each being right-handed or clockwise as viewed in the direction the current is flowing. The lines near the conductors are closed on themselves, but where they meet, they seem to absorb one another and each takes the path and continues the course of the other, which is the resultant path due to the

forces exerted by the separate fields. In the region between the conductors, it is seen that though the positive direction of the lines of force is in the same direction, at this point they are opposite, and each path by itself represents the direction a free north pole would move. Here then is like magnetism, and by the principle of resolution of forces, it is seen that the resultant will be something similar to the curves above.

In this illustration is seen the analogy of the lines of force to stretched rubber bands, there being a tension along the lines tending to draw the conductors together. The lines could be imagined to be replaced by one line joining A and B such that if all resistance to motion was overcome the conductors would be drawn together.

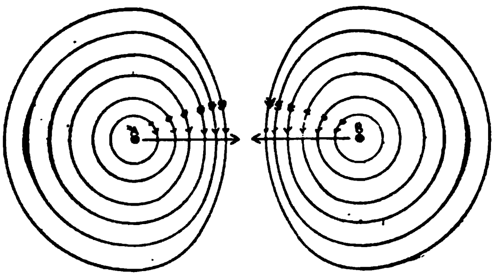


FIG. 31.—Magnetic Field of Parallel Conductors in Opposite Directions.

Fig. 31 shows two parallel conductors A and B, the current in A flowing away from the observer with its right-handed or clockwise field as viewed in the direction the current is flowing, and the current in B flowing towards the observer with its left-handed or anti-clockwise field as viewed in the direction opposite to that in which the current is flowing.

By the resolution of forces, it is seen that there is mutual repulsion between the fields in the region between the conductors, each field being compressed on its own conductor. The action of the two fields is such that there is compression across the lines of force while yet tension in the direction of their length.

As in the above case, the fields could be imagined to be replaced by a band in a state of compression which would cause the con-

ductors to be pushed apart if the resistance to compression was overcome.

The resolution of the forces acting in the two cases is shown by the following sketch:

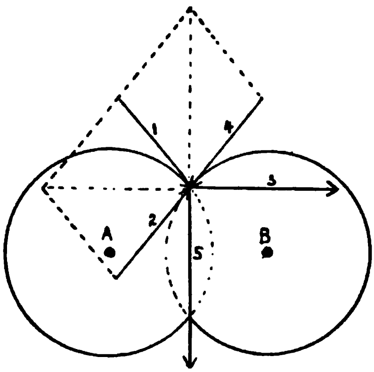


FIG. 32.—Resolution of Forces Due to Magnetic Field

In Fig. 32 one line of force is taken to represent the field of *A*, and the north pole travelling in this line at a given instant is travelling in the direction represented by arrow 1, tangent to the circle of the line of force. At a similar instant, a free pole in the field of *B* is moving in the direction of arrow 2, both being clockwise. The resultant of these two forces is arrow 3, which is in a direction parallel to *AB*, or the line described by a pole tends to embrace both conductors, giving the resultant line as seen in the preceding figure of attraction.

If, on the other hand, the field of *B* is opposite to that of *A*, at the instant a free pole in the field of *A* is moving in the direction of arrow 1, one in the field of *B* is moving in the direction of arrow 4, the resultant of which is arrow 5, which is in a direction perpendicular to *AB*, or a force which tends to separate the fields, causing a compression and a corresponding repulsion of the conductors carrying the currents.

If the conductors are not parallel, the reaction of the two fields will tend to bring them parallel and in such a parallelism that will tend to make both the currents flow in the same direction.

In the left-hand diagram of Fig. 33, the fields due to the two currents would tend to cause the upper and lower halves of each conductor to approach one another so that the two conductors would be parallel and both currents flowing down. In the right-hand diagram, the right and left halves of each conductor would tend to approach each other, so as to make the conductors parallel, with the current flowing from right to left.

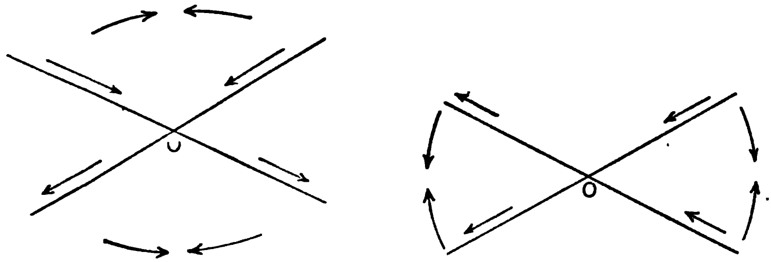


FIG. 33.—Oblique Currents.

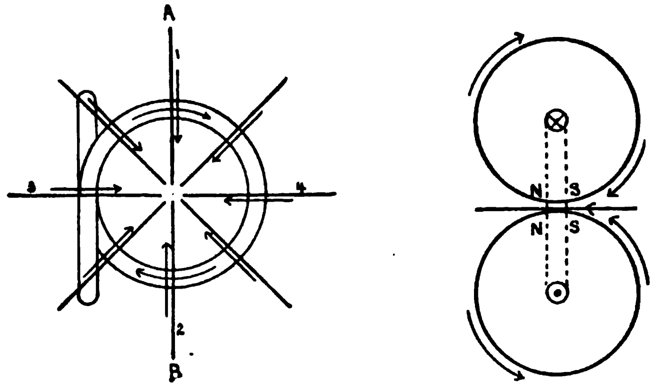
Magnetic Field Due to Current in a Coiled Conductor.

Having seen how the magnetic field is produced by a current flowing in a straight conductor, we are now in a position to take up the field produced by a current flowing in a conductor bent into a ring or spiral. In this case the magnetic field still surrounds the conductor as a series of whirls of lines of force, at any position the plane of the lines being normal to the conductor. Bending the conductor into a ring has the effect of increasing the intensity of the field in the center of the ring, or region near it, as it concentrates the lines of force at that point.

Figs. 34 and 35 represent a conductor carrying a current bent into a circle, one turn being made. Fig. 34 shows the current in the conductor flowing in a clockwise direction, and the lines radiating from the center show the projections of the magnetic lines surrounding the conductor, the positive direction, according to previous laws, being towards the center in the half of the circle that is nearer the eye. The magnetic lines are only those due to the ring of the conductor, not the straight portions of the conductor.

Fig. 35 shows a section of the conductor on the line AB, and revolved to the right 90°. The lines of force 1 and 2 are projected

as circles, 3 and 4 as a straight line and any intermediate lines as ovals. These latter are left out for the sake of clearness. The cross in the upper little circle ⊕ represents the tail of the arrow showing the direction of the current in the conductor, and the dot in the lower little circle ⊙ represents the head of the arrow. Remembering these directions, it is seen that the upper line of force has its positive direction in a clockwise direction and the lower in an anti-clockwise direction as shown by the arrows, and the inner portion of the center line is in the same direction.



FIGS. 34 and 35.—Magnetic Field Due to Coiled Conductor.

Remembering that the positive direction of these lines is the direction a free north pole would move, it is evident in the center it would move to the left, all the lines of force urging it in that direction. From the first law of magnetism, magnets of unlike polarity attract, and of the like polarity repel. As this free north pole would move to the left away from the left-hand side of the conductor, it is evident that that side must act as north polarity. Viewed from the right the current is flowing clockwise, which gives the rule: *If a spiral conductor carrying a current be viewed end on, and the current is flowing in a clockwise direction, then the nearer face is of south-seeking polarity and the further of north-seeking polarity.*

The right-hand face of the right-hand figure acts then as though it were a magnetic shell of south-seeking polarity and the opposite

face of north-seeking polarity. In the left-hand figure, the plane of the conductor nearer the eye is of south-seeking polarity and the farther side is of north-seeking polarity.

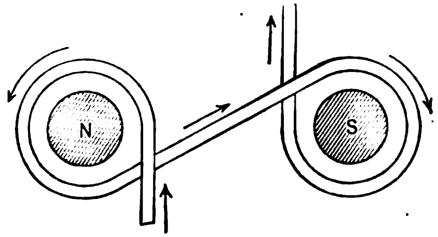


FIG. 36.—Two Core Polarity.

The rule given for determining the condition of polarity holds good for either a right-handed or left-handed spiral, as indicated in Fig. 36, showing opposite polarity produced in two cores by a single winding.

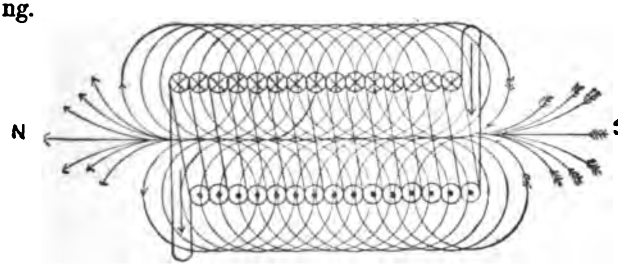


FIG. 37.—The Solenoid.

The Solenoid.

Fig. 37 represents the resultant magnetic field due to a conductor carrying a current, the conductor being bent into a number of turns, forming a spiral. The field is exactly similar to the case of one turn with the exception that the spiral forming the path is much longer, with the result that the field in the interior along the length of the spiral is almost uniform. Of course, if the conductor is bare, the turns must not touch in forming the spiral, but it is immaterial if the conductor is properly insulated.

Such a spiral is called a solenoid, and it acts exactly as an air magnet, reasoning as above showing the left-hand face to be of

north polarity and the right-hand face of south polarity. The intensity of the field in the interior is greatest at the center, gradually weakening towards the conductor. Only lines of force in the center are shown, but these are not the only lines, others being parallel to the center line in the interior and close to the inside of the conductor. At the ends, the lines of force spread out, the field weakening as the distance from the ends increases.

Magnetizing Force Due to a Solenoid.—It has been shown that a magnet of strength m placed in a magnetic field of intensity H is acted on by a force of

$$F = mH \text{ dynes.}$$

If the pole is of *unit* strength and moved through a distance l the work done, expressed in ergs, is

$$Fl = Hl. \tag{1}$$

The work done in moving a conductor carrying a current through a magnetic field is equal to the *current times the number of lines cut,* or

$$\text{Work done} = \frac{CN}{10} \text{ ergs.} \tag{2}$$

C is divided by 10 in order to reduce the number of amperes of current to the number of absolute units, as the work done is expressed in ergs.

From each unit pole there radiate 4π lines of force and each of these lines will cut each turn of the wire around the solenoid, as the unit pole is moved against the magnetic force. If there are S turns in the solenoid, the total number of lines cut is

$$N = 4\pi S,$$

and the total work done is

$$\text{Work done} = \frac{4\pi CS}{10} \text{ ergs.} \tag{3}$$

If the length of the solenoid is l, that is, the length occupied by the winding, the work done against the magnetic force, is, according to equation (1) $= Hl$, and therefore (1) $=$ (3), or

$$H = \frac{4\pi CS}{10l}.$$

This is an expression for the intensity of field within a solenoid due to a current flowing in it, and is also the magnetizing force of the solenoid.

Open and Closed Magnetic Circuits.

A **closed magnetic circuit** is one in which the lines of force due to the magnet flow around a *complete* iron path; an **open magnetic circuit** is one in which the paths of the lines of force are broken by one or more air gaps. The *open* circuit exhibits *free* magnetism and produces and can induce definite polarity and is sometimes called a *polar* circuit, while the *closed* circuit possesses practically no free magnetism and produces induction in neighboring magnetic substances only by the *leakage* of magnetic lines from it.

The ordinary bar magnet and the solenoid are examples of open magnetic circuits, and forms of open circuits are extensively used with continuous currents while closed circuits find their greatest uses in alternating currents.

The Electromagnet.

When no current is flowing through the conductor forming the solenoid, there is no magnetizing force to produce a magnetic field, either in the space surrounding the solenoid or in the column of air enclosed by the solenoid. When current flows, producing a magnetizing force, the column of air inside is subjected to a magnetizing force, producing a field of intensity H, and also an induction B. The coefficient of permeability $\mu = \frac{B}{H}$, of air $= 1$, as the induction B by definition is equal to H for the substance, air.

If, however, the conductor forming the solenoid is not wound around a column of air, but around a substance of high permeability, as soft iron, the number of lines of induction B that now thread through the iron is very much increased, and the intensity of magnetization of the iron is μ times the intensity of the air field H. Suppose there were 50 lines of force per unit of area in the air column, and the coefficient of permeability was 300, then there would be 15,000 lines per unit of area in the iron core.

Such an arrangement of solenoid and soft iron core is termed an **electromagnet**, the iron core exhibiting the properties of a magnet to its fullest extent only when current is flowing.

An electromagnet is a contrivance intended to exert a force of attraction on a movable piece of iron called the *armature*. Polarity

is induced in this armature by the magnetic field of the electromagnet, after which attraction takes place, the armature being made movable so it can approach the core of the electromagnet. Before induction can take place, there must be free magnetism, so the primary condition is that the magnetic circuit must be an *open* one.

The design of electromagnets depends on the character of work they are expected to do, whether they are to be *slow* or *quick-acting*, and whether the range of motion of the armature is to be *short* or *long*.

Examples of Electromagnets.—A very common and typical form of electromagnet is shown in Fig. 38.

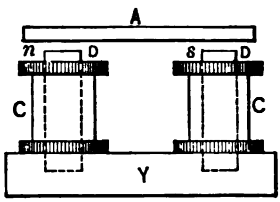


Fig. 38.—Typical Double-Coil Electromagnet.

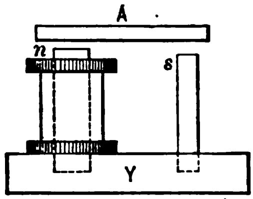


Fig. 39.—Club-Foot Electromagnet.

This consists of two coils of fine wire, *C*, wound oppositely on two bobbins which are slipped over the iron cores, *D*, which are secured to the base of magnetic material, *Y*, called the *yoke*. When current is sent through the coils, poles of opposite polarity are produced in the ends of the cores, *D*, the open magnetic circuit being through the two cores and the yoke. Above the upper ends of the cores is secured the *armature*, *A*, of soft iron, and so pivoted that it can approach the cores. It is made large enough to project slightly over the whole area of the cores which are usually circular. The free poles in the ends of the cores induce opposite polarity in the ends of the armature, after which attraction takes place and the armature moves towards the cores and brings up against them, forming a closed magnetic circuit. The armature will remain attracted as long as current flows, but when it is broken, the magnetic field is dissipated and the armature is usually provided

with some arrangement by which it is returned to its original position.

This form of electromagnet is very common and is used largely in vibrating bells, relays, and like appliances.

Fig. 39 shows a one-coil electromagnet, known as a **club-foot** electromagnet.

This differs from the two-coil electromagnet in that it only has one coil, the magnetic circuit being completed through the other core which is unwound, and which has the same polarity as the lower end of the wound core and the yoke. Its action is the same as the two-coil type.

This saves the winding of one magnet but diminishes the pull on the armature.

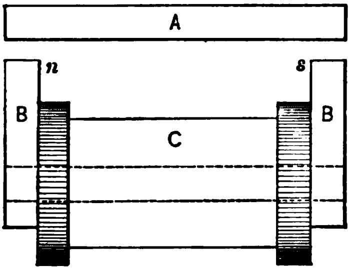


FIG. 40.—One-Coil Electromagnet.

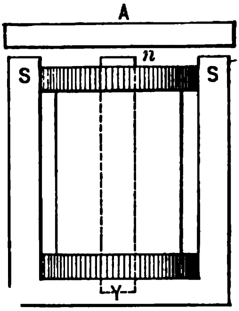


FIG. 41.—Iron-Clad Electromagnet.

Fig. 40 shows another and very common form of a **one-coil** electromagnet.

In this form the core forms the yoke and is fitted with two end plates, *B* and *B*, secured to it, in which opposite poles are produced. These poles in turn induce opposite polarity in *A* and the armature is attracted. This is a very compact form and is used largely in resistances for starting motors and other appliances.

Fig. 41 shows another form of one-coil electromagnet, known as the **iron-clad** type.

In this form the iron core is secured to and inside the bottom of a pot, and on the core is slipped the bobbin containing the winding. The upper end of the core forms one pole while the whole

upper rim of the pot forms the other, and the armature consists of a disc or lid of the same diameter as the pot.

All the foregoing types of electromagnets are examples of forms capable of exercising a strong pull over a short range.

For a weak pull over a long range, the ordinary solenoid with a movable core is used, as shown in Fig. 42.

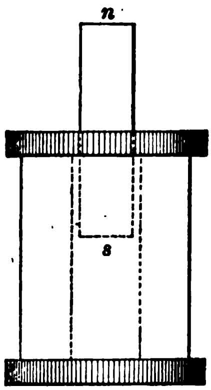


FIG. 42.—Long-Range Electromagnet.

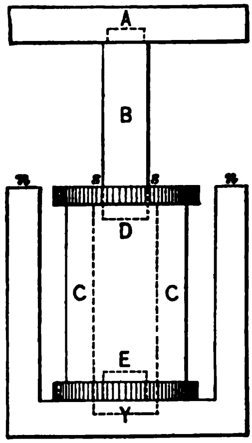


FIG. 43.—Stopped Solenoid.

When current is sent through the coils of this electromagnet, the core is sucked into the coil and the pull is greatest when the entering end reaches the further end of the coil. The pull in this form is not nearly as great as the form of Fig. 37, but the range of motion is very much increased.

Double Magnetic Circuit.—A modification of the above is shown in Fig. 43.

In this the magnetizing coil is slipped over a short core, *E*, which is secured to the yoke, *Y*, which is also provided with two limbs, *n* and *n*. The armature, *A*, is of the ordinary shape and is secured to a core, *B*, which is sucked into the coil when current is turned on. The dimensions are such that the bottom of *D* comes up against the top of *E* just when the armature brings up against the limbs *n* and *n*. This arrangement produces a double pull as the

magnetic field is divided, as the magnetic lines through B and E divide at the yoke and pass through the limbs n and n then through the ends of A to B again.

These last two forms are used in the mechanism of electric arc lamps and in some forms of automatic starting resistances for electric motors.

Magnetic Circuit.

By a magnetic circuit is meant the path of the magnetic lines of force, and it has been shown that these lines tend to make closed curves, either passing entirely through magnetic substances or partly through them and partly through air. Whatever the form of the magnetic circuit, its function is to direct the lines of force and the material of the circuit governs the resistance offered to the flow of the magnetic lines. Although these lines have no material existence, yet they can best be explained by their analogy to the electric current and considered as actually *flowing* in the magnetic circuit. In the magnetic circuit there is a leakage of the lines of force just as in the electric circuit there is a leakage of current.

The *total number of lines* in a magnetic circuit is generally referred to as the **magnetic flux.**

Magnetic Potential.—It has been shown that an electric current cannot exist in a conductor unless there is a *difference of electric potential* between the ends of the conductor, and there can be no magnetic lines of force produced unless there is a *difference of magnetic potential.*

Magnetic potential is measured by the work done in moving a unit magnet pole against the magnetic forces, and it has been shown that the magnetizing force due to a solenoid is

$$\text{work done} = \frac{4\pi CS}{10} \text{ ergs,}$$

where C = current in amperes,

S = number of turns of conductor on the solenoid.

As the magnetic potential is equal to the work done against the magnetic forces, it follows that it is equal to the magnetizing force of the current, or

$$\text{the magnetic potential} = \frac{4\pi CS}{10}.$$

To complete the analogy to the electric current, the magnetic potential is given the name **magnetomotive force,** and is defined as that force which tends to force magnetic lines through a magnetic circuit. It is designated as M. M. F.

The expression for M. M. F. contains only the variable factors, C and S, and is therefore directly proportional to their product CS, an expression which is called **ampere turns.** Experiment shows that as long as the number of ampere turns is constant, the M. M. F. will be constant; that is, one turn of conductor carrying 100 amperes will produce the same magnetization or M. M. F. as 100 turns carrying one ampere. It is also immaterial how far apart or how close together the turns are wound, the resulting M. M. F. will be the same.

Law of Magnetic Circuit.—Just as in the electric circuit, we have the law that

$$\text{total current} = \frac{\text{total E. M. F.}}{\text{total resistance}},$$

in the magnetic circuit we have

$$\text{total number of lines} = \frac{\text{total M. M. F.}}{\text{total magnetic resistance}}.$$

The total number of lines of force that a given magnetomotive force can force through a magnetic circuit depends on the magnetic resistance of the circuit, and this magnetic resistance is called its **reluctance.**

The magnetic law can now be stated in words, **that the magnetic flux in any magnetic circuit is directly proportional to the magnetomotive force and inversely proportional to the reluctance,** or in symbols,

$$N = \frac{\text{M. M. F.}}{Z}.$$

Reluctance.—This property of a magnetic material depends not only on the substance itself, but on its dimensions, varying directly as its *length* and inversely as its *area of cross-section.* It also varies inversely as its *permeability,* the higher the permeability, the less its resistance to the magnetic lines. For any portion of a magnetic

circuit, the reluctance of any portion is given by the expression

$$Z = \frac{l}{\mu a},$$

where $Z =$ reluctance,
$l =$ length of the path in centimetres,
and $a =$ cross-sectional area in square centimetres.

If, as generally the case, there are air gaps in a magnetic circuit, the reluctance of the whole is much increased, due to the low permeability of air; the reluctance also depending on the dimensions of the air gap.

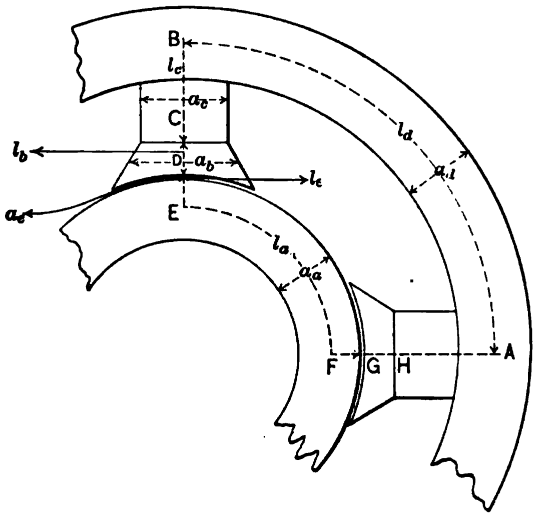


FIG. 44.—Typical Magnetic Circuit.

Joints also increase the reluctance, the amount of increase being a matter of experiment for each particular kind of joint.

Great heat increases the reluctance, but the temperature at which this is manifested is very seldom met in ordinary magnetic circuits.

Typical Magnetic Circuit.—In many combinations of electromagnets there are one or more magnetic circuits, but the data for each one may be determined separately, and the total joint effect

calculated. Examples of magnetic circuits will be shown later under the head of fields of dynamos and motors, but a typical circuit is inserted here.

Fig. 44 shows a typical four-pole magnet frame, in which there are four closed magnetic circuits. One of these fields is represented by the dotted line, through the magnet frame, the core pieces, the pole pieces, the air gaps, and the armature.

If $a =$ area of cross-section of the different parts shown,

$l =$ length of corresponding parts,
$\mu =$ coefficient of permeability of corresponding parts,

then the reluctance

$$\begin{aligned}
&\text{from } A \text{ to } B &&= \frac{l_d}{\mu_d a_d}, \\
&B \text{ to } C \text{ and } A \text{ to } H &&= \frac{l_c}{\mu_c a_c}, \\
&C \text{ to } D \text{ and } H \text{ to } G &&= \frac{l_b}{\mu_b a_b}, \\
&D \text{ to } E \text{ and } G \text{ to } F &&= \frac{l_e}{\mu_e a_e}, \qquad \mu = 1 \text{ for air.} \\
&E \text{ to } F &&= \frac{l_a}{\mu_a a_a}.
\end{aligned}$$

If all the magnetic parts of the circuit are of the same material $\mu_a = \mu_b = \mu_c = \mu_d$.

If the magnetic field is due to a current of C amperes with S turns, then the full expression between the magnetomotive force, the reluctance, and the total number of lines N is, assuming the same material,

$$N = \frac{4\pi CS}{10\left(\frac{l_a}{\mu a_a} + \frac{2l_e}{a_e} + \frac{2l_b}{\mu a_b} + \frac{2l_c}{\mu a} + \frac{l_d}{\mu a_d}\right)}.$$

To this denominator should be added the reluctance of the joints, which being known by experiment N can be calculated for a given number of ampere turns, or N being known from the E. M. F. to be generated, CS the necessary number of ampere turns can be calculated.

Residual Magnetism.

Suppose a piece of soft iron which exhibits no, or practically no, magnetism is made the core of a solenoid. When current is sent through the solenoid, the core at once evinces strong magnetic properties, due to its permeability. If now the solenoid current is turned off, it is found that the soft iron will now show magnetic properties, although in all other respects it is the same as before. The magnetization that is left in the iron is called **residual magnetism,** and the property of acquiring residual magnetism is called **retentivity.** The amount of magnetism retained after the magnetizing force is removed is called **remanence.** If the magnetizing current is reversed, the remanence disappears and if the current is the same as before, the core will be as highly magnetized with the opposite polarity. The force necessary to reduce the remanence to zero is called the **coercive force,** being a fraction of the total magnetizing force.

Certain substances show more residual magnetism than others, soft annealed iron showing much more than hard iron or steel, though the latter substances will hold their magnetism longer than the former, requiring a greater coercive force. Residual magnetism is greater when the current is gradually diminished, for when it is suddenly turned off there is a momentarily induced current of opposite direction which tends to destroy the residual magnetism. Mechanical shocks or changes of temper affect residual magnetism, especially in the softer varieties of iron, a gentle tap at times being sufficient to destroy it. Residual magnetism also gradually disappears in time, though varieties of hard iron or steel will nearly always show traces of it.

Measurement of Magnetic Fields.

In measuring the strength of a magnetic field what is desired is the total intensity of the field, and is calculated from the formula previously given

$$B = 4\pi I + H,$$

or

$$I = \frac{B - H}{4\pi}.$$

It is not necessary to make an exact measurement of the magnetic fields of dynamos on board ship, so the method of investigation will only be hinted at, exact methods requiring the use of instruments only found in laboratories. A small induction coil is connected to a ballistic galvanometer with its plane at right angles to the direction of the field. This is suddenly withdrawn to a place where the field is sensibly zero, when a deflection of the galvanometer needle is produced, owing to the current induced in the coil. This deflection is compared with the throw obtained by turning over quickly a large induction coil lying horizontally in the earth's field, this throw being proportional to the earth's vertical force.

It is frequently of importance to know how far the action of a magnetic field of a dynamo is felt from the machine, or to investigate the stray field of a generator; that is the lines of force that do not pass through the armature, and are not available for the induction of currents. This may readily be done by the vibration of an ordinary horizontal compass needle.

A compass needle when at rest, and only under the action of the earth's force, will point to magnetic north and if drawn aside from that position will vibrate from one side of north to the other, the arc of the angle described gradually lessening until the needle is again at rest and points north. During this time, the needle will make a number of vibrations depending upon the strength of the earth's horizontal force at that place. If now this same needle is made to vibrate in some other magnetic field, as the stray field of a dynamo, it will vibrate under the combined action of two forces, that of the stray field in addition to the earth's field. The square of the number of vibrations is proportional to the force under which the needle vibrates, and if the number of vibrations is counted for the same interval of time in the two cases, the forces are proportional to the squares of the number of vibrations in that time.

If n is the number of vibrations due to H, the earth's horizontal force, and n' the number due to the combined forces H' then $H' = \frac{Hn'^2}{n^2}$. The nearer n' approaches n the nearer H' approaches H. The needle may be vibrated at different distances from the dynamo or motor, and the combined forces of the earth

and machine may be calculated in terms of H, and the point noted where n' becomes equal to n, when $H' = H$, or the influence of the field has disappeared. This will give the distance in one direction where the stray field is zero, and the operation can be repeated in different directions. In making these experiments, the field of the machine should be excited to its fullest magnetization so the extreme distance will be known at which any external field exerts influence.

CHAPTER VIII.

ELECTROMAGNETIC INDUCTION.

Induction as used in electromagnetism may be defined as the mutual reaction that takes place between a magnetic field and a current of electricity flowing in a closed conductor lying in the influence of that field. It is immaterial in what manner the field is produced, and it may even be produced by the current of electricity itself, in which case the mutual action takes place between the current and the field that is produced by it.

It has been shown that currents of electricity flowing in closed conductors set up around the conductors magnetic fields, which are uniform in strength as long as the current is steady. Unless influenced by some external magnetic disturbance, the magnetic lines will be constant in number, direction, and position just as long as there is no change in the strength of the current. The intensity of this field will change as the current starts, stops or in any way alters its rate of flow.

If now there is a closed conductor without current, and by any means external to the conductor, a magnetic field is set up around it, it will be found that there is indication of current in the conductor as long as there is any change in the intensity of the field around the conductor. When once the field around the conductor is constant, then indication of current in the conductor ceases, although the field still surrounds it.

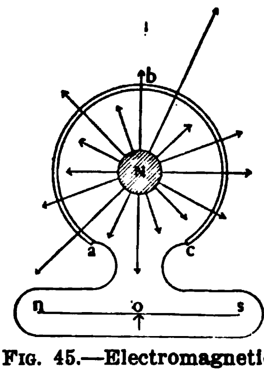


FIG. 45.—Electromagnetic Induction.

Suppose we have a closed conductor *a, b, c,* of the shape shown in Fig. 45, the circuit being completed around a small compass needle *n, s,* pivoted at *O,* the whole so arranged that the conductor

and connecting wires are parallel to the needle. If a pole of a permanent magnet *N* is thrust into the ring formed by the conductor, the magnetic lines due to this magnet spread out as shown in the figure, some passing through the conductor and others passing through the space enclosed by it. This magnetic field reacts on the conductor, setting up around it a magnetic field which in turn produces a current in the conductor. This process is called **induction,** and the current induced is manifested by the needle, *n, s* being deflected, due to the induced current flowing around it. This induced current is only noticed during the time that there is relative motion between the field of the magnet and the conductor, for as soon as the magnet is held steady in any one position, although the intensity of the field remains the same, there is no manifestation of current. The energy of pushing the magnet towards the conductor has been converted into electric current and when the magnet is at rest, there is no energy expended and no currents induced.

If the magnet was held steady and the conductor pulled away from it, there would be the same phenomenon exhibited, except that the needle would be deflected in the other direction. Approaching the south pole would produce a current in the opposite direction from that induced by the approach of the north pole.

The nearer that the pole is approached to the plane of the conductor, the greater is the deflection of the needle, showing greater current induced as more lines of force from the magnet pass through the coil.

Fig. 46 shows how more lines would pass as the magnet is approached nearer and nearer.

This experiment illustrates the first principle of induction, showing that **currents are induced in closed coils through which lines of force of an external magnetic field pass, as long as there is such relative motion between them as to alter the number of lines that pass through the coils.**

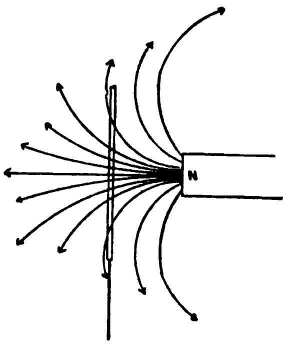


FIG. 46.

The direction of an induced current in a closed coil depends upon the direction of the lines relative to the movement of the conductor, upon the number of lines and whether the motion tends to increase or decrease the number of lines that pass through the coil. As it is important to know the direction of induced currents under certain circumstances, the rules for determining this direction or the laws of induction, as they are called, are given.

Determination of Direction of an Induced Current.—One of the simplest and most easily remembered rules is that given by Fleming, as follows: *Arrange the thumb and first two fingers of the right hand to point in three directions at right angles to each other. If the first finger points in the positive direction of the lines of force, and the thumb in the direction of the motion of the conductor, then then middle finger will point in the direction of the induced current.*

Laws of Induction.—1. A decrease in the number of lines of force that are cut by a closed coil produces a direct current, that is, a current of such direction, that if one looks along the positive direction of the lines of force, it will flow in the closed coil in the direction the hands of a clock move, or clockwise.

2. An increase in the number of lines of force that are cut by a closed coil produces an inverse current, that is, a current of such direction that if one looks along the positive direction of the lines of force, it will flow in the closed coil in a direction opposite to that of the hands of a clock, or anti-clockwise.

3. The E. M. F. generated is proportional to the rate of decrease of the number of lines of force cut.

If the N pole of the magnet referred to above is thrust into the ring at right angles to the plane of the paper from the near side of the paper, there is an increase in the number of the lines that pass through the coil and the observer on this side of the paper is looking along the positive direction of the lines of force, so the resulting current is inverse or anti-clockwise as viewed by the observer. The effect of this induced current is to make the near side of the coil a magnetic shell of north polarity. We then have the effect of a north pole approaching a north pole, which produces repulsion between them and which is manifested by its requiring greater force to thrust in the magnet as it approaches the coil.

In pulling away the magnet (N pole) from the coil or the coil from the magnet (N pole), there is a decrease in the number of lines of force that pass through the coil, and still looking along the positive direction of the lines of force from this side, the resulting current is direct, or clockwise, tending to make this side of the coil a shell of south polarity. We have now the effect of a north pole being pulled away from a south pole or vice versa, causing an attractive force between them, which is manifested in the greater force required to separate them.

Lenz's Law.—This phenomenon of induced currents is summed up in Lenz's law, which states that "**in all cases of electromagnetic induction, the induced currents have such a direction that by their reaction, they tend to stop the motion which produces them.**"

Illustration of Induction.

As a further illustration of the laws of induction suppose we had a circular closed coil lying in a magnetic field, the plane of the coil being at right angles to the lines of force and so arranged that the coil could be revolved about the extremities of one of its diameters.

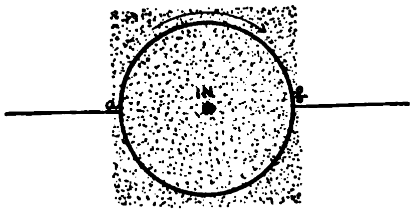


FIG. 47.—Illustration of Induction.

In Fig. 47 the lines of force are represented by the dots running through the paper, the observer on this side looking along the positive direction of the lines. As long as there is no movement of the coil, there is no induced current. Imagine the coil to be revolved on the axis a, b, the upper half turning into the paper, then there is a decrease in the number of lines that pass through the coil, and from the first law of induction, the induced current should be in the direction shown by the arrow. Now the converse of this

is also true, and if a current flows in the direction of the arrow, then the resultant field, within the coil, has the direction shown by the positive direction of the lines. A free north pole would be repelled from this side of the paper, showing that this side is of south polarity, a fact previously shown as due to a clockwise current. The field due to a current flowing in the conductor in the direction of the arrow is not the same as the imaginary field above consisting of parallel straight lines, but the resultant field, within the coil, may be imagined to be represented by one line, shown by the heavy dot and marked *IN,* that being its positive direction.

From the above it is seen that there is the same relative connection between the directions of the lines of force and the resulting induced current as there is between a steady current and its resultant field.

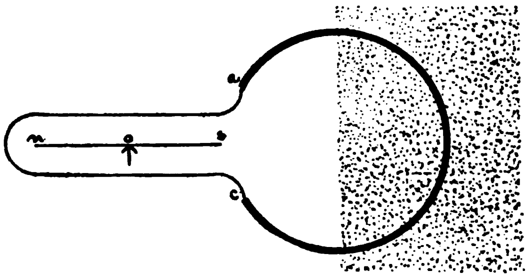


FIG. 48.—Illustration of Induction.

If, instead of approaching a magnet with its lines of force issuing in all directions to our closed coil, suppose we imagine this coil to be thrust into a uniform magnetic field as represented in Fig. 48.

The magnetic field is represented as before by the dots, and the observer is looking along the positive direction of the lines of force. As the closed coil *a, c* is moved from left to right into and at right angles to the magnetic field, there is an induced current in *a, c* due to the change in the number of lines that pass through the coil. It has already been noted that for the induction of current, there must be a *change* in the number of lines passing through the coil. If the coil is moved up and down the plane of the paper while lying in the field, there will be as many lines entering the coil on

one side as are leaving it on the other, so there will be no change and no induced current. Similarly, if the coil while parallel to the plane of the paper is moved up and down through the paper, there will be no induction. The above phenomenon is noticed when there is no change of intensity of the field, for if the number of lines at any portion is greater than at another, there will be a change in the number of lines passing through the coil, and so there will be induction of current.

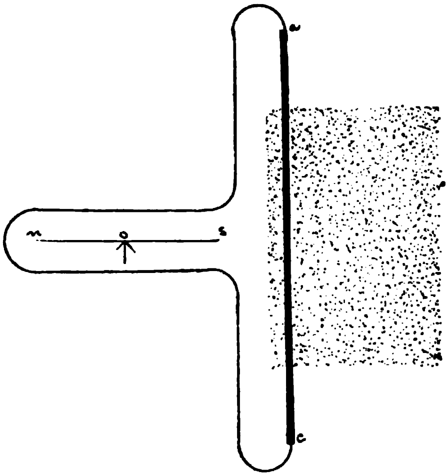


FIG. 49.—Illustration of Induction.

If the coil while lying at right angles to the lines was revolved about one of its diameters, there would be induction, for the number of lines that passed through the coil would then vary from a maximum to a minimum.

Suppose now the conductor *a, c* instead of forming a closed coil is straightened out and forms a long straight conductor, so in the sense we have been speaking, there is no closed coil. This is represented in Fig. 49.

If this straight conductor *a, c* is moved from left to right at right angles to the magnetic field and into it, it will be found that there is an induced current precisely as in the case where the conductor was bent into a circular coil. Here the induced current

cannot be said to be due to the change in the number of lines that pass through the coil, for there is no coil, but the current is induced by the conductor *cutting* the lines of force. If the conductor is moved parallel to the lines there is no cutting and no current.

This illustrates the principle of induction that **a conductor moved across a magnetic field so as to cut the lines of force, there is an E. M. F. generated which tends to produce an induced current in that conductor.** If the cutting be made continuous a continuous induced current will be the result.

The distinction between the currents induced in a conductor by a change in the number of lines that pass through the coil and by a conductor cutting across lines of force is not so sharp as it might appear. The induced current in either case is due to the same movement, and every conductor carrying a current forms part of a closed circuit, and while a conductor may be cutting lines of force, yet those lines must be passing through a closed coil of which the conductor is part, and the lines are passing into and out of the coil at the exact rate that the conductor is cutting them. The distinction is made between the two, as some examples of induction are better explained by one method and others by the other, and the application of both should be understood.

In either case, it is not a current that is generated, but rather an E. M. F. and we speak of the generation of E. M. F. and the induction of current, the latter following as a result of the former.

Different Methods of Induction.

As a result of induction, an E. M. F. may be generated in a closed conductor, or currents may be induced in it, by three different methods; that is, by electromagnetic induction, by self-induction and by mutual induction.

In **electromagnetic induction,** as already explained, the change in the number of lines of force which pass through the closed conductor is due to some relative movement between the conductor and the magnetic field. This is the underlying principle of all dynamo electric machines.

In **self-induction,** the change in the number of lines of force is caused by changes in the current that is producing the field, and

any change produces a corresponding E. M. F. which opposes that change and which tends to keep the current at a constant strength. In dynamos and motors self-induction takes place in the coils of the armature that are passing under the brushes, in the positions in which the current is reversed, or is dying out, or starting in the other direction.

In **mutual induction**, there are two or more closed conductors, in which any change in the field of one due to any change in its current acts on the other to increase or decrease its field, and consequently its current. The action is mutual: one acts or reacts on the other. This is the principle of the transformer or induction coil, or of a dynamo in which there is no moving part, the number of lines cut by one conductor being caused by changes of current in the other.

Self-Induction.

This is a case of induction in which an electric reaction takes place between a magnetic field and the electric current which produces the field. This action prevents the instantaneous rise and fall of a current in a closed conductor. While the phenomenon of self-induction is almost imperceptible in the case of a simple conductor carrying a current, yet the principle may be pointed out by means of a straight single current and the magnetic field brought into existence by it. It has been shown that the magnetic field due to a current flowing in a straight conductor surrounds the conductor as a series of concentric rings or whirls, the number of lines of force remaining constant as soon as the current reaches a steady value; the number increasing or decreasing with the current. When there is no current there is no magnetic field, but as soon as the faintest current flows, the lines of force are brought into existence. These lines of force may be considered as waves expanding from the very center of the conductor as a source of disturbance, and in their expansion they thread through or cut the conductor, and here is produced a simple case of electromagnetic induction, there being relative motion between the conductor and the field produced by the current. This current induced by the field, which in turn is produced by the original current, is in the opposite direction to that

of the original current and tends to weaken it, or to delay the current in reaching its maximum value.

As long as the original current is increasing, the lines of force are expanding as a series of waves and the current is being constantly retarded by the induced current, but as soon as the current becomes steady, there ceases to be relative motion between the field and the conductors and the induction ceases.

If the current becomes weakened the lines of force tend to collapse on the conductor, and this cutting of the conductor by these lines induces a current in the same direction as that of the original current, and which tends to keep the current from weakening. If the current is suddenly stopped, there is a quicker motion to the lines of force and this induced current may have an instantaneous appreciable value.

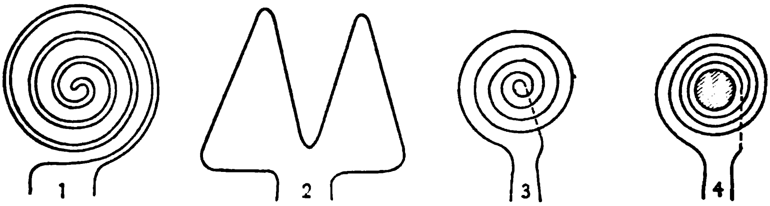


FIG. 50.—Forms of Self-Induction Circuits.

The E. M. F. of the momentary induced current may have a value considerably higher than that of the original current, and it is this high E. M. F. which produces the spark noticed whenever a circuit is broken, for the induced current tends to flow, though the original current be broken, and the high E. M. F. generated tends to bridge over the circuit where broken, volatilizing portions of the metal circuit and maintaining an arc for a brief interval across the space where the circuit is interrupted.

Forms of Inductive Circuits.—The amount of self-induction of an electrical circuit depends on its geometrical form. Fig. 50 shows some forms of typical circuits.

Type 1 shows that a current entering one of the terminals flows as many times around the helix in one direction as it does in the opposite direction, and in consequence the magnetic field set up by

one series of convolutions is counteracted by that of the other series and there is practically no self-induction. This is known as a non-inductive resistance and the *double winding* is used for the coils of standard resistances.

Type 2 shows very little self-induction but type 3 shows more. If the conductor of type 3 be made of many turns of wire close together, the effect of self-induction may be very marked. It will be still more marked if these turns are wound on an iron core, as type 4, as in the case of an ordinary electromagnet, for then there are many more lines of force due to the permeability of the metal. The lines of force in expanding from and collapsing on the conductor as the original current is increased or decreased, not only cut the portion of the conductor from which they emanate, but also the turns lying on either side for a considerable distance, so the total effect is that of all the lines of force due to each turn cutting a great many of the other turns.

Coefficient of Self-Induction.—The number of lines of force produced by a current is directly proportional to the current in a region where the permeability of the surrounding medium is constant, and any change in the current produces a proportional change in the number of lines of force.

A circuit has unit inductance when a rate of change of current of one C. G. S. unit per second produces one C. G. S. unit of E. M. F. One C. G. S. unit of E. M. F. is produced by the cutting of one line of force per second. Hence, the elements of current and number of lines are connected by the inductance, L, and since the number of lines is proportional to the current, we have the following relation:

$$L = \frac{N}{C}.$$

This coefficient, L, is constant for all values of C and depends on the form of the circuit. In a magnetic substance, the permeability varies with the current, and therefore L will vary with the degree of magnetization.

If a coil has S turns, the total cutting of magnetic lines is SN, and

$$LC = SN.$$

The E. M. F. of self-induction is proportional to the rate of change of current, and in a coil of inductance L, the E. M. F. is equal to $-LdC/dt$, where dC/dt is the rate of change of current. The current flowing due to this E. M. F. is $-LdC/dt \div R$, where R is the resistance in circuit. Consequently the effective current, on making a circuit, is

$$C = \frac{E}{R} - \frac{LdC}{Rdt}.$$

The value of C after an interval t is obtained by integration, which gives a value of

$$C = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right)$$

where e is the base of the Naperian system of logarithms.

The factor L/R is called the *time constant*, and is denoted by T, and the expression for the current becomes

$$C = \frac{E}{R}\left(1 - e^{-\frac{t}{T}}\right).$$

C is the value of the current t seconds after closing the circuit.

Physically the time constant represents the time in seconds from the instant of closing the circuit required to attain the $e - 1/e$ part of its final value E/R. Thus in a circuit of 1 henry inductance and 1 ohm resistance, $T = L/R = 1$; that is 1 second after closing the circuit, the current will be $1.718 \div 2.718 = .632$ of its final value.

It is frequently difficult, and sometimes impossible, to calculate the inductance of coils without iron cores, though several empirical formulæ have been used for the different forms that coils may have. With complete iron magnetic circuits so arranged that it may be assumed that all the magnetic lines pierce all the turns, the calculation becomes comparatively simple, if the permeability of the iron be known. Thus in a ring of soft iron of mean circumference l, area of section A and permeability μ, overwound with a layer of copper wire of S turns through which there is a current of C amperes, the number of lines, or magnetic flux, is

$$N = \frac{4\pi CS\mu A}{10l}, \text{ or}$$

$$L \text{ in henries} = \frac{SN}{C} = \frac{4\pi S^2\mu A}{10^9 l}.$$

A must be expressed in sq. cm. and l in cm. to allow the above equation to be correct.

If the falling off in the flux near the ends of a long helix be neglected, the inductance of such a helix without an iron core may be calculated from the same formula for a coil with a complete iron circuit. The intensity of field inside a long helix is expressed, as shown on page 132, by

$$H = \frac{4\pi CS}{10l}.$$

The total flux, $N = HA$, and, as before,

$$L = \frac{SN}{C};$$

hence

$$L = \frac{4\pi^2 r^2 S^2}{10^9 l} \text{ henries.}$$

Mutual Induction.

The phenomena of self-induction and mutual induction are explained by the same electrical principles; self-induction being manifested in a closed conductor, the induction taking place in itself, while in mutual induction, the induction takes place in some adjoining separate closed circuit. However, the phenomenon of mutual induction may be accompanied by self-induction.

Suppose there are two parallel conductors, A and B, Fig. 51, each forming a portion of a closed circuit. If in A current is established from some outside source, the usual magnetic field will be set up around it. As current flows, the lines of force will expand as waves from the conductor as a source of disturbance, and if the current is flowing in the direction marked IN, the positive direction of the lines of force would be clockwise as shown by arrow 1. These waves expand, provided the current in A increases, until the conductor B is reached which up to this time has no current flowing in it. Immediately B acts as a new center of disturbance and a series of waves expand from it, the positive direction,

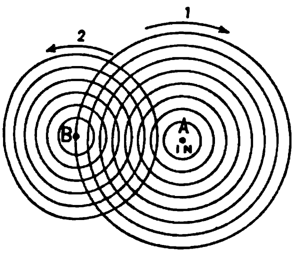


FIG. 51.—Illustrating Reversal of Current Due to Induction.

however, being now opposed to that due to *A*. Setting up these lines around *B* has the effect of inducing a current in *B* which is in existence until the current in *A* becomes steady. A change of current then in *A* has resulted in a momentarily induced current in *B*, but of the opposite direction.

It is impossible to depict by diagram just how or why this reversal of the positive direction of the lines of force takes place, when the current in one is increasing, but if the analogy of the lines of force to water waves be accepted, it is readily shown.

But first suppose, however, that the current in *A* is steady and that the field due to this current embraces or surrounds *B*. If the current in *A* is now weakened, the lines of force surrounding *A* will collapse on *A* and in doing so will cut through *B*, which will become a center of disturbance of another series of lines, which will expand as long as those of *A* collapse, but which will disappear as soon as the current in *A* becomes steady. This is shown in Fig. 52. The lines of force of *B* will in this case have the same positive direction as those of *A*, showing that the induced current in *B* is in the same direction as the original current in *A*.

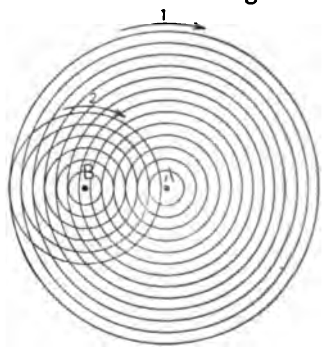


FIG. 52.—Illustrating Reversal of Current Due to Induction.

The following figures, 53, 54, 55, and 56, are intended to show how in one case the direction of the wave lines, the lines of force, are in the opposite direction to the original lines and in the other case how they are in the same direction.

Fig. 53 represents a wave as emanating from *A* and travelling in the direction of its normal, shown by the long arrow towards *B*; that is, it is expanding. The wave front on the left is shown as striking an obstacle *B* and its onward motion carries the outer part onward, the part near the obstacle being retarded. The arrows show the positive direction of the lines due to the current in *A*. The wave front bends around *B* until it is torn apart, as it were, when the wave front unites, with its positive direction the same

as before, leaving a small wave around B in the opposite direction, as shown by Fig. 54, this small wave then expanding around B as the other did around A, but with diminished energy. Each succeeding wave from A is acted upon in the same manner, forming a succession of waves around B.

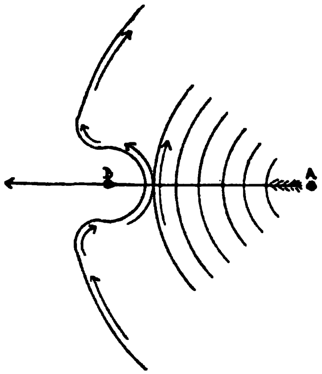


FIG. 53.

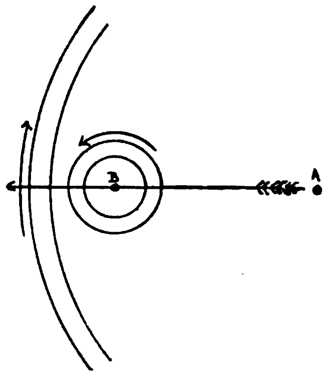


FIG. 54.

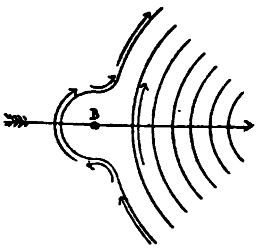


FIG. 55.

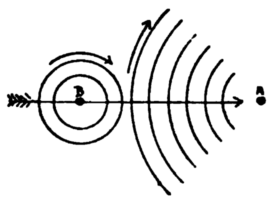


FIG. 56.

Fig. 55 represents a wave as emanating at A and travelling in the direction of its normal, shown by the long arrow; that is, it is collapsing on A. The wave front on the left is shown as striking an obstacle B. Similar to the above, it is shown that the small wave set up around B is of the same direction as the collapsing wave. This small wave expands around B as shown in Fig. 56, inducing a current that is in the same direction as the weakening current in A. Each succeeding wave collapsing on A is acted upon in the same manner, forming a succession of waves around B.

If both A and B have currents from some outside source flowing in them, any change in one will produce a change in its field which will react on the other, either increasing or decreasing its current as long as the change is taking place.

Coefficient of Mutual Induction.—This is defined as the number of lines of force *mutually* embraced, or are common to both circuits, when each carries unit current. If L_1 is the coefficient of induction of the first coil, called the *primary,* and L_2 of the second, called the *secondary,* then the coefficient of mutual inductance is

$$M = \sqrt{L_1 L_2}.$$

The coefficients of induction of each coil depends on the permeability of the surrounding medium, so, therefore does M, and the introduction of an iron core to the interior of one coil will greatly increase M.

Mutual induction plays an important part in the principle of many electrical devices for the conversion of E. M. F. into higher or lower values. Prominent among these devices are Alternating Current Transformers and Induction Coils.

Principle of Transformers.

As in the case of self-induction, the mutual induction between two closed circuits will be greatly increased by making the conductors in the form of helices and winding them on some strongly magnetic material like soft iron, and bringing the turns on one close to those of the other. If under these conditions a rapidly alternating current be sent through one coil, it will produce a rapid expansion and contraction of its field which will produce a corresponding change in the current in the other coil. By making one coil of a great many turns of very fine wire, a very high E. M. F. can be produced. By varying the size of the wire and number of turns in the two coils, a convenient method of changing the E. M. F. of a given source of supply is at hand.

The elementary form of transformer consists of a closed magnetic circuit, on which are wound the two coils, one called the primary; the other, the secondary, as shown in Fig. 57.

A and B are the terminals of the primary and C and D of the secondary. The primary may consist of many turns of fine wire to receive a small current at high E. M. F. and the secondary of a few turns of thick wire to give out a larger current at low pressure. Such a transformer would be called a "step down" transformer. If wound in the opposite sense, it would be called a "step up" transformer.

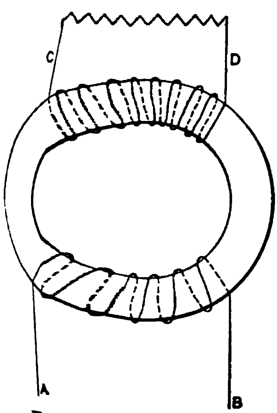


FIG. 57.—Typical Transformer.

Apart from the small losses in transformation, the *input* is equal to the *output*, and if V is the terminal E. M. F. and C the current of one coil and V_1 and C_1 of the other, then

$$VC = V_1C_1.$$

E and E_1, the total E. M. F's. induced in each coil are directly proportional to the number of turns in the two coils.

The relation between the voltages at the terminals is given by the following expressions:

$$V = E + Cr \text{ (for primary)},$$
$$V_1 = E_1 - C_1r_1 \text{ (for secondary)},$$
$$\frac{E}{E_1} = k \text{ (a constant depending on the relative}$$

number of turns) from which the relation of V to V_1 may be found.

$$V_1 = \frac{V}{k} - \left(\frac{r}{k^2} + r\right)C_1.$$

Induction Coils.

In the ordinary induction coil, it is not usual to use an alternating current, but a continuous current from a few cells, the change in the magnetic field of the primary coil being caused by making and breaking the circuit. The primary coil is connected in series with a condenser, which has the effect of making the "*break*" more rapid and opposing the current at "*make*."

The connections of a simple induction coil circuit are shown in Fig. 58.

A represents the magnetic core around which are wound the two coils, the primary from the battery *B;* the secondary being wound over it, and carefully insulated. The terminals of the secondary coil are shown at *a, b.* The continuous current from the battery is interrupted at *I,* a pivoted conductor, which makes contact either with *K* or is drawn away from it towards the core *A.* When *I* makes contact with *K* and current from the battery flows around the primary coil, *I* is attracted to the core, breaking the circuit at *K.* As soon as the circuit is broken, the core ceases to be magnetic and

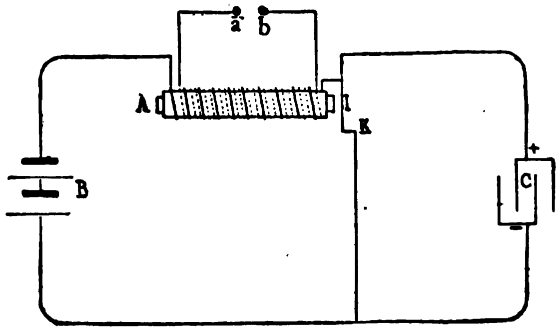


FIG. 58.—Circuit of Induction Coil.

I makes contact again with *K,* when the circuit is re-established. This constitutes the make and break and the alternating field produced in the core induces an alternating current in the secondary coil, the current being manifested by a spark jumping from *a* to *b.*

The E. M. F. of the secondary coil depends on the rate of change of the magnetic field of the primary coil, as $E = -\frac{dN}{dt}$, where *N* is the number of lines of force. *N* depends on the primary current and *t* on the number of makes and breaks. When the interrupter *I* is attracted towards the core and the circuit is broken, the induced current produced by the break would ordinarily cause a spark to jump from *I* to *K,* but by introducing the condenser in circuit, this extra induced current flows into it, charging the upper plate positively, the lower, negatively. These charges

immediately recombine, flowing through the primary and battery, thus reducing the battery current at the time the circuit is again made, and demagnetizing the core. This action increases the time of the "*make,*" while reducing the time of the "*break,*" making the latter quicker and sharper, the result of which is a high E. M. F. in the secondary. The terminals *a* and *b* can be so arranged that the spark due to break can jump across, while that due to make cannot, thus making a steady stream of sparks.

Induction Coils for Creating Electric Oscillations.—In most systems of wireless telegraphy an induction coil is used in the creation of electric oscillations necessary for the formation of electromagnetic waves, and the following description is of a type suitable for such work:

Induction coils are known by their size, thus a 10-inch coil means that it will produce in air a spark 10 inches long between the terminals of the secondary coil. A coil of the above size would consist of 300 to 400 feet of insulated copper wire, wound around an iron core consisting of a bundle of soft iron wires about 2 inches in diameter. The secondary would consist of 12 to 15 miles of very fine double-covered silk copper wire, depending on the diameter, making 45,000 to 50,000 turns, wound over the primary. The winding of the secondary is made in a large number of sections, each section prepared separately and each carefully insulated with paraffin and discs of shellaced paper. A large number of such sections varying from 100 to 500 are slipped over a thick ebonite tube, inside of which is the primary coil and iron core.

When the coil is in operation great differences of potential exist in the coils of the secondary and this must be so wound that no two parts, which are a great difference of potential, are near together. There must also be perfect insulation between the primary and secondary coils, and it is usual to have them separated by a tube of ebonite at least half an inch thick covered with a layer of paraffin an inch thick.

When the sections of the secondary coil are assembled on the insulating tube they are compressed and immersed in molten paraffin. This is done on a former, after which the whole secondary winding is enclosed in a cylinder of ebonite and thick ebonite cheeks

are fitted on the ends of the ebonite tube on which the secondary is wound.

The completed coil may be then enclosed in a wooden box which is filled with insulating oil or filled in solid with paraffin, the ends of the secondary being brought out through ebonite tubes.

If the coil is to be used with an interrupted continuous primary current, a condenser is placed across the point of rupture of the primary current, its action being previously described.

In some forms of induction coils, the primary is wound in sections and the ends of each brought out in such a manner that the various sections can be joined in series or in parallel so as to vary the resistance and inductance of the coil, as well as the effective number of turns.

Problems on Inductance.

1. Find the inductance of a primary coil of 100 turns and secondary of 10 turns, wound on an iron ring of 20 cm. mean diameter and 10 sq. cm. section, the permeability of the iron being 700.

2. A transformer is wound with 50 turns in the primary coil and 1000 in the secondary. The magnetic circuit has a mean length of 50 inches and an area of 12 sq. inches. Assuming a permeability of 1800, what are the inductances of the two coils? What is the mutual inductance?

3. If 1000 volts are impressed on a circuit of 10 henries inductance and 4 ohms resistance, what will be the value of the current at the end of 1/120 second, at the end of 1 second? What the final value?

4. A coil of wire has an inductance of .025 henry and a resistance of 25 ohms, and a current of 25 amperes is flowing in it. The current is suddenly stopped and dies to zero in .005 second. What is the momentary value of the induced E. M. F?

CHAPTER IX.

ELEMENTARY THEORY OF THE ELECTRIC GENERATOR.

An electric generator, or simply a generator, is a dynamo electric machine constructed for the purpose of converting mechanical energy into electric energy by the induction of E. M. F. in a closed coil moved in a magnetic field.

Referring to the chapter on the Derivation and Definition of Units, the C. G. S. unit of E. M. F. is defined to be *that E. M. F. produced by the cutting of a magnetic field of one gauss intensity by one centimetre of the conductor moving at a velocity of one centimetre per second.*

In Fig. 59, the straight wire AD is fitted to slide along the portions AB and CD and to form portion of a closed circuit $ABCD$. The whole circuit is placed in a uniform magnetic field of intensity H, perpendicular to the plane of the paper with the positive side on this side of the paper.

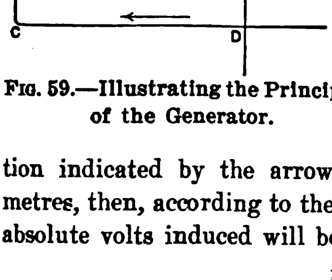


FIG. 59.—Illustrating the Principle of the Generator.

If AD is moved to the right at a velocity of v centimetres per second, there will be an E. M. F. induced in the conductor which will create a current in the direction indicated by the arrows. If the length of AD is l centimetres, then, according to the definition of E. M. F., the number of absolute volts induced will be

$$E = Hlv.$$

The E. M. F. induced produces a current which is urged across the magnetic field; the C. G. S. unit of current existing *when each*

centimetre of its length is urged across a magnetic field of unit intensity with a force of one dyne.

From Lenz's law it is seen that the work done in producing the induced current opposes the action which produces it, and the total force urging the conductor across the magnetic field is

$$F = HlC \text{ dynes.}$$

The work done on the conductor against this force is Fv ergs and which must be equal to the electric work produced, or

$$Fv = HlCv,$$

or

$$\text{work done} = EC \text{ ergs per second}$$
$$= EC \text{ watts.}$$

In the generator, then, work is supplied by an external agency moving a conductor across a magnetic field and continually overcoming a force which tends to stop it. The greater the current induced or the greater the intensity of the field, the greater the force to be overcome and the greater the power necessary to be supplied. Due to the mechanical construction of the generator, the force overcome is a tangential pull applied at the radius of the armature, and the product of the two factors, *force* and *radius,* is called **the torque** on the conductors. If the conductor is supplied with an E. M. F. this drag on the conductor would cause the conductor to move in the opposite direction and the generator then becomes a motor.

Expression of Induced E. M. F.—In t seconds the wire AD moves over a space equal to vt and cuts lvt square centimetres. If the intensity is H; or, in other words, if there are H lines of force per square centimetre, the total number of lines cut is $Hlvt$, and since $E = Hlv$

$$E = \frac{N}{t},$$

where N = total number of lines or magnetic flux.

This shows that the induced E. M. F. is equal to the rate of cutting of the lines of force, or the *E. M. F. in C. G. S. units is equal to the number of lines of force cut per second.*

Induced E. M. F. in a Closed Coil.

In Fig. 60, N and S represent the north and south poles of a magnet, either permanent or electromagnetic, producing a magnetic field that is represented by the lines running from one to the other, the arrowed heads representing the positive direction of the lines of force. In this field and lying at right angles to the lines of force is a rectangular loop of wire, its open ends being connected to a voltmeter, thus making a closed circuit, and capable of rotation round an axis represented by the broken line.

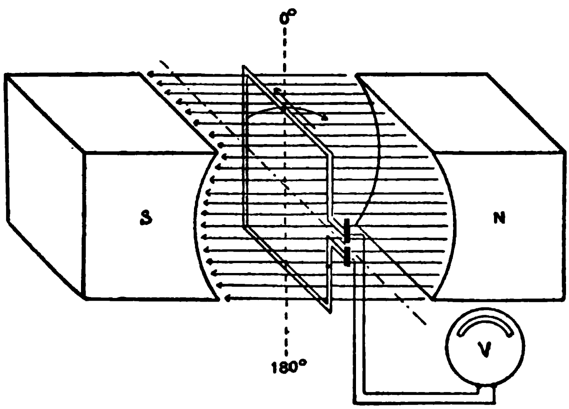


FIG. 60.—Induced E. M. F. in a Closed Coil.

As this coil lies at rest in the field there is no reaction between them, and the voltmeter indicates zero. In this position, being at right angles to the lines of force the greatest number of lines thread through the loop. As the coil is revolved as shown by the curved arrow to the right, the number of lines that thread through the coil constantly diminishes in the proportion of the angle turned through from 0°. If N is the total number, then at any angle θ, the number that threads through the loop is $N \cos \theta$, and at 90°, or when the loop is laying parallel to the lines, the number is a minimum. As soon as the coil is revolved so as to cut the lines of force, an E. M. F. is generated and it will be indicated on the

voltmeter and if the coil is turned at a constant speed this E. M. F. will increase until the 90° position is reached when it is a maximum. Now applying the laws of induction, we see in what direction the resultant current is; for imagine the eye in the face of the north pole and looking along the positive direction of the lines of force. The voltmeter end of the coil will then be on the left hand. As the coil turns, the number of lines of force is decreased, and a decrease means a direct current or clockwise current when looking along the positive direction of the lines of force. In this case, the current would flow in the direction indicated by the straight arrow. As the coil passed the 90° position, there would be an increase in the number of lines, which should produce an inverse current, or anti-clockwise, as viewed by the same observer, but now he is looking at the other side of the coil, or what was the top is now the bottom, so, though it is anti-clockwise as he views it, it is really in the same direction in the coil as before. The E. M. F. will gradually decrease from 90° to 180°, where it will again be zero, and this will be indicated on the voltmeter.

It must be remembered that the E. M. F. is not only proportional to the number of lines cut, but to the rate at which these lines are cut. At the 0° and 180° position, the greatest number of lines are being cut, but there the E. M. F. is least, and at 90° the lines thread through the coil at the greatest rate, at uniform speed, and here the E. M. F. is greatest, or the number of lines threading through at any time is $N \cos \theta$, and the rate of cutting is $d(N \cos \theta) = - N \sin \theta$, which is in accordance with the third law of induction, the minus sign indicating the decrease. The sine function varies from 0 to unity, or the E. M. F. at 0° is $\sin 0° = 0$ and at 90° is $\sin 90° = 1$, or proportional to these limits. Continuing the motion from 180° to 270° results in a direct current, or clockwise, and this is in direct opposition to the current in the first half of the revolution. From 270° to 0°, the current is inverse as viewed from the same place, but the coil now being turned over is in the same direction as from 180° to 270°.

The final result then of one complete revolution of the coil is generation of E. M. F. and induction of current, starting at 0° with both a minimum and increasing to a maximum at 90°, then

decreasing again, the current being in the same direction to 180°. From this point everything is reversed, the E. M. F. and current increases to a negative maximum, and then decreases to 0° as the original position is occupied. This result is both in accordance with the theory as deduced from the laws of induction, and is actually shown on the voltmeter, on passing the 180° position, the deflection of the needle being reversed.

As the E. M. F. is proportional to the rate of cutting, the faster the coil is turned, the greater will be the maximum E. M. F., and greater in proportion at any intermediate position.

It may be noticed that it is stated that the lines of force thread through the loop formed by the coil and the number of lines of force that do this first increase and then decrease. This is simply a convenient way of expressing the fact that the lines of force are actually cut by the coil in its revolution, and the mere fact that the lines of force thread through the loop would not necessarily mean a generation of E. M. F. It should also be noticed that the sides of the coil, the up-and-down connections, although they pass through lines of force, do not alter the number cut, so there is no E. M. F. due to these parts of the coil; they simply act as conductors to complete the circuit.

Induced E. M. F. in a Closed Surface.—If this coil were replaced by a thin sheet of conducting material, the action and resulting current would be the same, with the exception that every part of the thin sheet would cut lines of force and the current would circulate in all parts as small eddies, having a resultant effect of one large current, and would be reversed in exactly the same way as in the case of the coil. In this case also, there would be a real increase and decrease in the number of lines that pass through the sheet as well as an increase and decrease in the number of lines cut.

Curve of E. M. F.

As the E. M. F. generated in the preceding demonstration increases from 0 to a maximum, then decreases to 0, and increases again to a negative maximum and then again to 0, there must be some constant relation between the E. M. F. generated and the

time of revolution. The relation is represented by the curve of sines, as the E. M. F. is proportional to $d(N \cos \theta) = - N \sin \theta$, and θ depends on the rate of revolution. The curve of sines is the resultant motion of a particle that is acted on simultaneously by two motions, one a simple harmonic motion in a straight line and the other a uniform motion at right angles to it, and on account of its identity with the curve of E. M. F. its construction is given in Fig. 61.

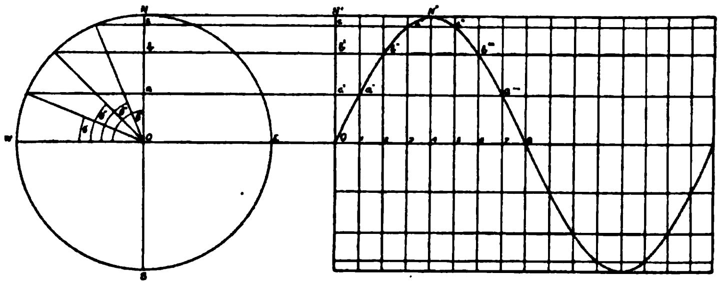


FIG. 61.—Curve of E. M. F.

Curve of Sines.

If a particle W revolves in the circle $NESW$ at a uniform rate, in equal times it will pass over equal arcs of the circle, and if the points at which the particle arrives at the end of equal intervals of time be projected on a diameter of the circle, the motion of these points on the diameter will constitute a simple harmonic motion.

The curve of sines has been defined as the resultant motion of a particle that is acted upon simultaneously by two motions, one a simple harmonic motion and the other a uniform motion at right angles to the simple harmonic motion.

The simple harmonic motion is represented as taking place in the line NOS, the points a, b, c, and N being the projections of the points arrived at in the circle by a particle that is uniformly revolving in it, the equal intervals of time in this case being 1-16 of the time of one revolution. The uniform motion is taking place in the line WOE. In equal times the uniform motion carries the

particle to the right equal distances, and the equal distances between the vertical lines are arbitrarily chosen to represent the distance carried.

Let the particle be at o'; it is acted upon by two motions, a simple harmonic motion in the line $N'O'S'$ and the uniform motion in the line WOE. If the particle was acted upon by the simple harmonic motion alone, in 1-16 of the time of one period, it would be at a'. If acted upon by the uniform motion alone, in the same time corresponding to 1-16 of a period of the simple harmonic motion it would be at 1. As it is acted upon simultaneously by these two motions, in 1-16 of a period, it would be at a'', describing the path $o'a''$. Similarly in a time represented by 2-16 of a period, in its simple harmonic motion it would be at b', and due to the uniform motion, it would be at 2, and as they act together, it would be at b'', describing the path $o'a''b''$. Similar reasoning will show how the points $c''N''c'''b'''a'''$, 8 are determined, and a curve drawn through these points will show the resultant path of the particle. As the particle in its simple harmonic motion passes through O', going towards S', the uniform motion still acting, the part of the curve below the median line is described. When the particle has completed 16-16 of its period in its simple harmonic motion, it has been carried to the right 16 equal distances, and the particle is in a position to repeat the described curve.

Properties of the Curve.—The ordinates of the curve are proportional to the sines of the angles described by the particle in its uniform motion in the circle, the motion of this particle representing the motion of the coil in the elementary dynamo. $a''1$ is proportional to sin θ', $b''2$ to sin θ'', etc. If the height of the middle ordinate $N''4$ is unity, as the sine of θ'''' or 90° equals 1, the heights of the other ordinates will represent, in terms of the middle ordinate, the sines of the angles formed at the center of the circle.

The abscissæ are proportional to the time during which the uniform motion acts, and which time being proportional to the arc of the circle swept over in the same time, is proportional to the sines of the angles thus described. As the ordinates are pro-

portional to the sines of the angles, and the time to the sines of the angles, the equation of the curve must be $y = \sin x$, the axis of Y representing sines and the axis of X, time. The area included between one quarter of the curve and the median line is

$$\int_0^{\frac{\pi}{2}} y dx \text{ or } \int_0^{\frac{\pi}{2}} \sin x dx, \text{ or area} = -\cos x \Big]_0^{\frac{\pi}{2}} = -(0-1) = 1.$$

As the length of the median line for a quarter of the curve is $\frac{\pi}{2}$, the average value of the ordinates must be the area divided by the base or $\frac{1}{\frac{\pi}{2}} = \frac{2}{\pi}$; or, in other words, the average value of the sine function from 0° to $\frac{\pi}{2}$ must be $\frac{2}{\pi}$, or 7-11. Also the average value of the heights of the ordinates must be $\frac{2}{\pi} \times$ the height of the maximum ordinate.

In one revolution then of the coil in the elementary dynamo, the average E. M. F. is 7-11 of the maximum E. M. F.

The Act of Commutation.

It has been shown how a coil revolved in a magnetic field has an E. M. F. generated in it, and a current induced, and how in one revolution the current grows to a maximum, then decreases to a minimum, and then has the direction of the current reversed and the phenomena repeated. In continuous-current dynamos it is necessary that there be some means provided by which the current is made to flow in one direction in the external circuit, while it is reversed in each revolution in the internal circuit. This is effected by means of a *commutator* and the operation is called the *act of commutation.* Each end of the coil is secured to a segment of a circle, made of some conducting material, the segments being separated by air gaps or some insulating material. These segments taken together constitute the commutator, on which rests the brushes, which collect the current for the external circuit. Just how the reversal is effected will be explained by small sketches showing the position of the coil in different stages of the revolution.

Fig. 62 represents the loop lying in the magnetic field between the pole pieces *N* and *S*, the lines of force running from *N* to *S*, and being omitted for sake of clearness. This loop is perpendicular to the lines of force and in the 0° position, the brushes being shown as just touching both segments of the commutator and connected to the external circuit marked *R*. One-half of the loop is shown as a double line, being connected to its segment of the commutator, also double; the other half of the loop with its segment being shown as shaded, and they will be referred to as *double* and *shaded.*

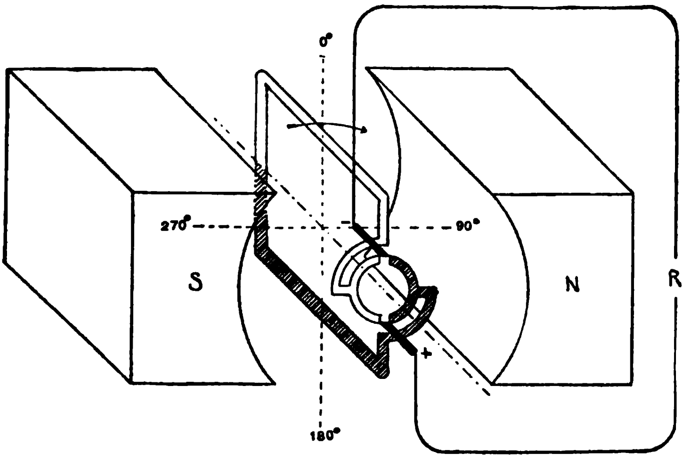


FIG. 62.—Act of Commutation, Coil at 0° Position.

In this 0° position, there is no E. M. F. generated and no current induced. As soon as the coil is revolved in the direction of the curved arrow, E. M. F. is generated, and by the laws of induction current is induced and flows from double to shaded in the internal circuit, and from shaded to the external circuit through the + brush and from the external circuit to double through the — brush. This condition is shown in the next figure.

In Fig. 63 the pole pieces have been removed but are supposed to be in the same position as in the first figure. This represents the loop in a position shortly after revolution has commenced, a

position a little in advance of the 0° position. A direct current as viewed by an observer looking along the positive direction of the lines of force is induced, or to the observer it is clockwise and flows from *double* to *shaded* in the internal circuit, from shaded to the external circuit through the + brush and from the external circuit to double through the — brush. The direction of the currents is indicated by the arrow heads. The brushes of course remain stationary. When the revolving coil passes the 90° position, the

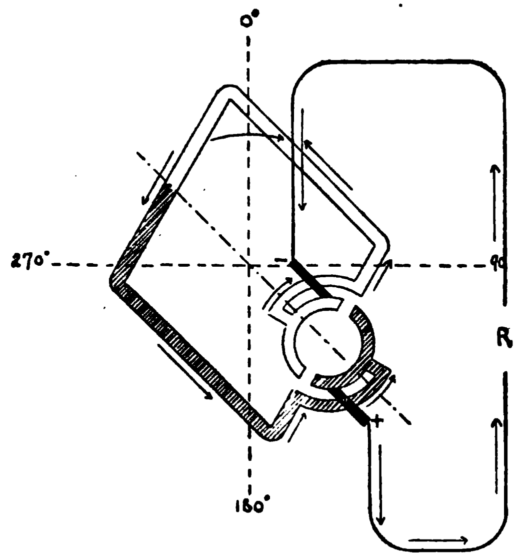


FIG. 63.—Act of Commutation, Coil Passed the 0° Position.

shaded half is then uppermost, and there is an inverse or anti-clockwise current as viewed by the same observer, as there is now an increase in the number of lines of force cut, but the coil being turned over a direct current on one side and an inverse on the other makes the current in one real direction, and from 0° to 180°, the current in the internal circuit will be from double to shaded.

This position of the loop (Fig. 64) shows it just before the 180° is reached. The current in the internal circuit is still from *double* to *shaded* and the external current remains as before. . The current

is weakening as this position is reached and when it reaches the 180° position, it will be the same as in the first figure, with the exception that the coil is simply turned over and the current both in the internal and external circuits has died out, and the brushes will just touch both segments of the commutator. Further revolution from the 180° position will reproduce the phenomena of induction as in the 0° position with the exception of the coil being turned around. Following from 180° is shown in the next figure.

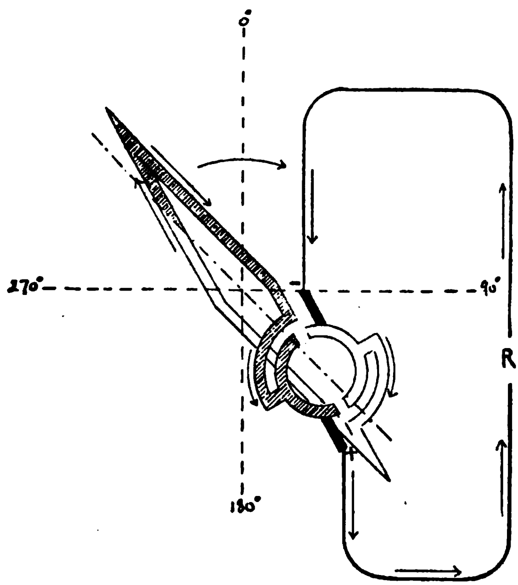


FIG. 64.—Act of Commutation, Coil Approaching the 180° Position.

Fig. 65 represents the coil just after the 180° position is reached. There is now again a decrease in the number of lines of force cut, and a direct current for the same observer, but now the coil being turned half way around, the current flows from shaded to double in the internal circuit, from double to the external circuit through the + brush, and from the external circuit to shaded through the — brush. Thus it is seen that though the actual direction of the current in the coil is reversed, by means of the commutator the

direction of the current in the external circuit remains the same as before, and as far as its direction is concerned, it is continuous, which is the sole object of the commutator. The current will increase in intensity until the 270° position is reached. From that position to the 0° or 360° position, there is an increase in the number of lines of force cut, or an inverse anti-clockwise current as viewed by the same observer, but what is now clockwise will

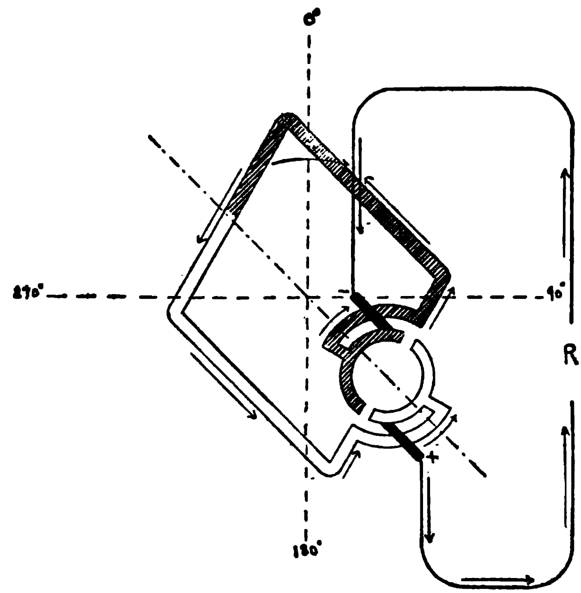


FIG. 65.—Act of Commutation, Coil Passed the 180° Position.

then be anti-clockwise and the real direction of the current in the internal circuit will be the same from 180° to 360°.

Fig. 66 represents the loop just before the 0° or 360° position is reached. The current is now anti-clockwise as explained under the previous figure, but is still from shaded to double. The current is decreasing as the 360° position is approached until that is reached when the current has died out entirely, and the loop is in its original position, each brush just touching both segments of the commutator.

To summarize then: The current is nothing at 0°, then gradually approaches a maximum in both circuits until 90° is reached, then decreases to a minimum and becomes nothing at 180°, both currents having died out. From 180° both currents increase, the direction of the current in the internal circuit having been reversed, while the current in the external circuit remains the same as before. This increase continues until 270° is reached when

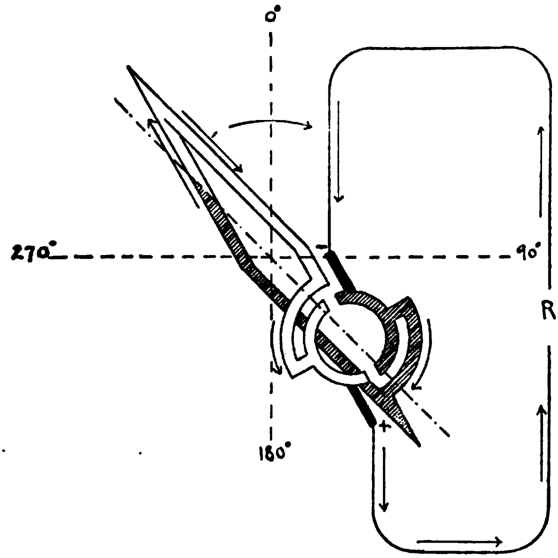


FIG. 66.—Act of Commutation, Coil Approaching the 360° Position.

both currents are at a maximum again and then decrease of both currents takes place until the original position is occupied when both currents have completely died out. Further revolution of the coil repeats the phenomena.

The Generation of an Increased and Steady E. M. F.

It has been seen that a simple rectangular turn without a commutator when revolved in a magnetic field so as to cut lines of force gives rise to a fluctuating E. M. F., which in its complete

revolution is represented by the ordinates of the curve of sines, as shown by Fig. 67. Two revolutions are represented.

If the coil is fitted with a commutator, the negative ordinates of the curve are commuted into positive ordinates as shown in Fig. 68.

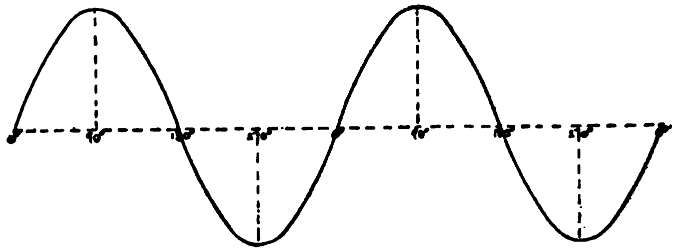


FIG. 67.—Curve of E. M. F. Before Commutation.

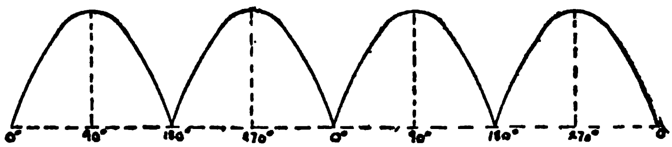


FIG. 68.—Curve of E. M. F. After Commutation.

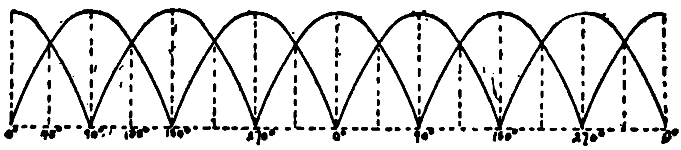


FIG. 69.—Curves of E. M. F. Due to Two Coils.

If, in addition to the simple turn, there is another turn placed at right angles to the first and connected to its own segments of the commutator, and entirely independent of the first turn, it will exhibit the same phenomena and give rise to the same curve of E. M. F. with the exception that it will differ in phase by one-quarter of a period, or the curves will differ in their maxima and minima by 90°. The result of two turns 90° apart is shown by Fig. 69, showing when one is in position of maximum cutting of lines of force, the other is in the position of minimum cutting.

If these two turns be connected in series with one another, or in other words, if the same length of conductor in the two turns be made into one coil with the two turns at right angles to each other, then the curve of E. M. F. in its entirety ceases to be the curve of sines, but the E. M. F. at any point is equal to the sum of the individual E. M. F's. at that point due to each turn alone.

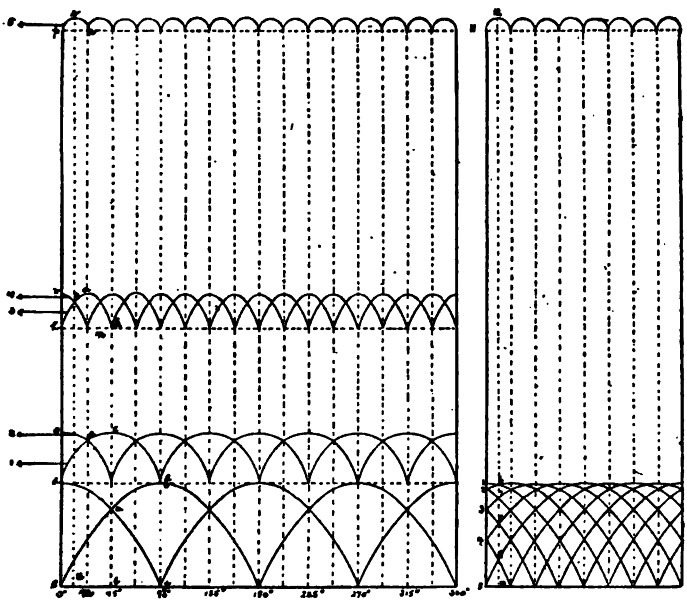


FIG. 70.—Curves of E. M. F. Showing Superposition.

In this case, the maximum E. M. F. would be at 45°, 135°, 225°, and 315°, and the minimum at 0°, 90°, 180°, 270°, and 360°.

The result of superimposing the two curves formed by each turn of the coil, the turns being at right angles to each other, is shown in curve 1 of Fig. 70. The height of the ordinates at 0° and 90° of curve 1 is equal to the height of the ordinates at 0° and 90° of the original curve of E. M. F., these being shown at the bottom of the left-hand portion of the diagram. The height of the ordinates at 45°, 135°, 225°, and 315° is each equal to the sum of the

ordinates at 45° of the original curves, or *bc* of the curve 1 is equal to $2 \times ab$.

Curve 1 then represents the E. M. F. due to one coil consisting of two turns at right angles to each other, connected in series, and has resulted in a mean E. M. F. of twice the original mean E. M. F.

If another coil consisting of two turns at right angles to each other, and connected in series, be placed at equal distances between the turns of the first coil, it will give rise to another curve similar to 1, marked 2, having its maximum value where the other is a minimum and vice versa. If these two coils, or four turns, be connected in series, the resulting curve of E. M. F. will be curve 3, *he* being equal to $oe + de$, and $nm = ne + em$, or $2 \times em$.

Curve 3 then represents the E. M. F. due to one coil consisting of four turns at angles of 45° to each other, all four turns connected in series, and has resulted in a mean E. M. F. of twice the value of curve 1, and four times the value of the E. M. F. due to one turn.

If again another coil consisting of four turns at 45° to each other, and connected in series, be placed at equal distances between the turns of the other coil, it will give rise to another curve similar to 3, and marked 4.

If these two coils, or eight turns, be connected in series the resulting curve of E. M. F. will be curve 5, *pe* being equal to $ve + he$, and *su* being equal to $st + tu$ or $2tu$.

Curve 5 then represents the E. M. F. due to one coil consisting of eight turns, at angles of $22\frac{1}{2}°$ to each other, all eight turns connected in series, and has resulted in a mean E. M. F. of twice the value of curve 3, four times the value of curve 1, and eight times the value of the mean E. M. F. due to one turn.

This process shows that the more conductors there are in series, the higher and steadier the E. M. F. and a point would eventually be reached when the curve would approximate a straight line, and this is really in fact the theoretical process of building up a drum-wound armature.

The same steadiness without the increased E. M. F. would be observed if the eight turns, or sixteen cutting conductors were each connected to their segments of the commutator without in any way being connected to one another. The resulting curves are

shown in the right-hand lower portion of the diagram, and it is seen that the E. M. F. is as nearly continuous as in the first case, but the E. M. F. is that due to one turn. If again these were all connected in series as before, the resulting curve of E. M. F. would be obtained at any point by addding together all the ordinates of the different curves at that point, and of course it should give the same curve as in the first case, where the additions take place separately. The height of the ordinate 5.11 is equal to $1.5 + 2 \times 2.5 + 2 \times 3.5 + 2 \times 4.5$, and 10.12 is equal to $2 \times 6.10 + 2 \times 7.10 + 2 \times 8.10 + 2 \times 9.10$.

Curve of Total E. M. F.

The curve of sines represents by the heights of its ordinates the E. M. F. at any instant of a single turn of conducting material revolved in a magnetic field in terms of the maximum ordinate as unity. The total E. M. F. due to the same turn in one revolution is the sum of all the ordinates, that is, the total E. M. F. from 0° to 45°, for instance, is the sum of all the ordinates from 0° to 45°, or is represented by the sum of all the sines of the angles from 0° to 45°. In other words, it is the integration of the equation of the curve from 0° to the point considered, or

$$\int_{0^\circ}^{x^\circ} \sin x dx = - \cos x \Big]_{0^\circ}^{x^\circ}$$

The curve of total E. M. F. from 0° to 360° is represented by Fig. 71.

Armature Cores.

So far in the consideration of the physical theory of the generator, the turn of wire was supposed to be revolved between the poles of a magnet, permanent or temporary, in the field produced by the poles, and without any mechanical connection with any other revolving part. It must necessarily be wound on some kind of support and to this support the general name of core is applicable. As far as mechanical considerations go, this core might be made of wood or brass or hard rubber, but electrical considerations show that it should be of some magnetic material, in order that the lines

of force may be drawn to and through it, or as it has been seen under *magnetic circuit,* in order that the reluctance of the magnetic circuit may be reduced. For a given magnetomotive force, due to the ampere turns of the field windings, the total number of lines, or flux, depends on the magnetic resistance, and the smaller this can be made, the greater will be the flux. The conductors must cut the lines of force and to do this they must thread through one side of the core and out the other. If the core were of some non-magnetic substance, the lines of force would tend to go around it rather than through it, its permeability being less than that of air,

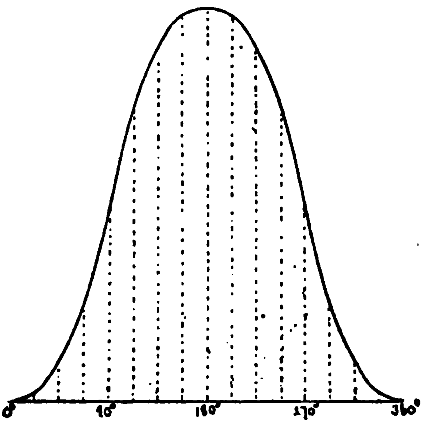


FIG. 71.—Curve of Total E. M. F.

the lines of force cut by the conductors being much reduced. Where a magnetic core is used, the magnetic circuit consists of the field frame, the pole pieces, the air gaps between the pole pieces and armature core, and the core itself. This shows, too, that the air gaps should be as small as possible, and the pole pieces should have a cross-section at least equal to the smallest cross-section of the magnetic circuit.

Eddy Currents.—The core, being magnetic, while revolving in the magnetic field is subject to the same laws of induction as the conductors themselves, and would have induced in its mass currents which would flow around and through it, and in any one cross-

section they would flow in the same direction. They follow the paths of least resistance in the core, thus giving rise to innumerable little complete circuits, to which the name of *eddy currents* is given. The effect of these currents is to heat the core, and being brought into existence by the power which revolves the armature they represent a distinct loss of energy. It is remembered that the induced current has a direction which is at right angles to the magnetic lines, and if the circuit of the eddy currents can be shortened in that direction their waste will be reduced. This is effected by cutting the armature core in thin slices in a direction parallel to its direction of rotation and to the lines of force and perpendicular to the direction of the induced currents. The thin slices or laminations are put together, being insulated one from the other, the effect being to reduce the eddy currents without increasing the magnetic resistance of the circuit. Any through connections there may be for holding the laminations together will have induced currents in them, but it is usual to have them well inside the core, where the field is weakest.

Calculation of Induced E. M. F.

The preceding curves show that an increased E. M. F. is produced by connecting up the single coils in series, so as to make one closed coil of many turns. The number of conductors on the armature then becomes one of the factors that determine the value of the E. M. F. generated. Under the definition of volt, it was seen that it was the E. M. F. induced when a conductor moves in a magnetic field at such a rate that it cuts 10^8 lines of force per second. The number of lines of force is then another factor of the generated E. M. F. The effect of cutting lines of force may be increased by increasing the speed at which the conductor moves, thus if a conductor moves at such a rate as to cut 2×10^8 lines of force per second, it will generate 2 volts and so on.

The three factors that determine the E. M. F. in a dynamo are (1) *the number of cutting conductors;* (2) *the number of lines cut;* (3) *the speed at which the lines of force are cut.*

Starting with the elementary coil of the drum armature in the 2-pole dynamo in a plane at right angles to the lines of force, it

embraces the total number of lines, which may be represented by N. If this rectangle or coil makes one revolution per second there are $2N$ lines cut per second by each limb of the coil, because each limb cuts the whole number of lines in each half revolution. If the coil makes n revolutions per second the number of lines cut per second by each limb is $2Nn$. If there are Z conductors all the way around the armature, or Z limbs, there are $\frac{Z}{2}$ limbs in series from brush to brush, or the number of lines cut by $\frac{Z}{2}$ limbs is $\frac{Z}{2} \times 2Nn = NZn$, or the average E. M. F. induced is $\frac{NZn}{10^8}$ volts, where

$N =$ total number of lines of force,
$Z =$ total number of conductors around the armature,
$n =$ number of revolutions per second.

In drum armatures, the number of limbs is twice the number of coils in each section, whereas in the ring armature, the number of limbs is equal to the number of coils in each section, and the same formula is applicable to both armatures. Z always represents the number of conductors counted all the way around the armature.

The average E. M. F. may be expressed in terms of angular velocity by putting $\omega = 2\pi n$ where $\omega =$ angular velocity and then

$$E = \frac{\omega}{2\pi} NZ.$$

In a time t, the angle θ turned through would be $2\pi nt$ and the number of lines enclosed by the rectangle at the angle θ turned through from zero would be $N \cos \theta$, and the rate of cutting would be the rate of $N \cos 2\pi nt = 2\pi nN \sin \theta$. The average of $\sin \theta^{\circ}$ between $0°$ and $90°$ is $\frac{2}{\pi}$, so the average

$$\text{E. M. F.} = 2\pi nN \times \frac{2}{\pi} = 4nN.$$

The number of rectangles is $\frac{1}{2}Z$ and the number of conductors in series from brush to brush is $\frac{1}{2} \times \frac{1}{2}Z$ or the final average E. M. F. $= 4 \times \frac{1}{4}ZNn = NZn$ as before.

Fundamental Equation of the Direct-Current Generator.—The above equations are adduced to apply to bipolar machines, but a more general solution for the value of the induced E. M. F. is given.

Let N = the number of magnetic lines that enter the armature from each north pole and leave at each south pole of the field magnets,
p = number of field poles,
Z = number of conductors on the outside of the armature,
p' = number of paths in parallel between brushes,
n = number of revolutions of armature per second.

In $\frac{1}{pn}$th of a second the armature will move the distance between two poles, or between the brushes and in this time will cut N lines of force. The conductors are then cutting at an average rate equal to $N \div \frac{1}{pn}$, or pnN lines of force per second. The average E. M. F. from brush to brush per conductor is pnN at any instant.

The number of conductors in series in each path between the brushes is $\frac{Z}{p'}$ and since the average E. M. F. per conductor is pnN, the E. M. F. between the brushes is $pnN \times \frac{Z}{p'}$, or

$$E = \frac{pnNZ}{p'}.$$

This equation applies to bipolar or multipolar machines, and ring or drum armatures with any kind of winding, the above expression giving the E. M. F. between the brushes in absolute units.

Points of Design.—In generators designed for use with direct-connected motive-power as with sets used on shipboard, the number of revolutions of the armature is limited by the speed that can be given to the engine and this is necessarily low. Increasing the number of conductors in series on the armature results in higher E. M. F., but at the same time adds to the resistance and to the self-induction, both of which are objectionable. Increasing the area of the armature conductors or making the core more massive

increases the number of lines cut, and this is one of the features of modern dynamos, the cores being very large and the conductors few and heavy. The greatest factor of the E. M. F. is undoubtedly the magnetic field, and this is the most practical way of increasing it. In modern machines, the field is made very strong and is divided up into many separate magnetic circuits, this having the advantage of increasing the E. M. F. and at the same time reducing armature reactions and distortion of the field, so there is very little necessity, if any, of changing the position of the brushes on changes of load.

Pole Pieces.

In most cases pole pieces are made of solid pieces of metal, cast in one with the frame or yoke or cast separately and bolted to the frame. In some designs the pole pieces are built up of laminated pieces, similar to the construction of armature cores.

The laminated construction insures a uniform quality of metal throughout the entire pole which tends to produce a better distribution of the magnetic flux and tends to insure equal magnetization of all poles. With a cast pole internal flaws and blow holes may increase the magnetic reluctance of one pole over another and cause electric unbalance in the completed machines.

The greater magnetic reluctance of rolled iron from which the laminated poles are built as compared with cast poles permits the use either of a smaller section of pole or of a less amount of copper to produce the same flux, which feature can be taken advantage of in design either to produce both a smaller and less expensive machine or else a machine of lower temperature rise without sacrificing any other desirable feature.

A laminated pole will build up much closer to the size prescribed in the design and the field coil can be wound with less internal clearance. It will likewise permit the field coil to have a uniform clearance all around the pole when required, thus affording a good space for radiating the heat generated in the field coil.

The laminated pole presents a laminated face to the armature and breaks up eddy currents with consequent heating and loss of efficiency which always must obtain in a solid pole face.

Armature Reactions.

When current flows in the armature of a generator, due to the conductors cutting the lines of force of the magnetic field, another magnetic field is brought into existence which reacts on the main flux. This field varies with the strength of the armature current, and thus with the same field flux, the actual active magnetic flux is different in a loaded machine from an unloaded one.

It can be shown that in order to obtain sparkless commutation, it is necessary to shift the brushes from the theoretical line of least induction to a position slightly in advance of this in the direction of rotation of the armature.

Considering a two-pole generator, the field flux induces poles of opposite polarity in the armature core in a line with the main pole pieces. The field due to the armature current induces poles of opposite polarity in the armature core in a line at right angles to the first. The necessary shifting of the brushes in the direction of rotation causes the line of polarity due to the armature current to shift in the same direction. The resultant of the two lines of polarities is thus shifted in the direction of rotation, causing a distortion of the field, making it stronger at one end of the pole piece and weaker at the opposite end, the field apparently being dragged around in the direction of rotation of the armature, and the stronger the current the greater the distortion.

The magnetomotive force due to the field produced by the armature current can be resolved into two forces, one in the direction of the main field flux and the other at right angles to it. The former acts against the main field flux, tending to weaken or *demagnetize* it; the other acts across it and tends to *cross* magnetize it. The more the brushes are moved in the direction of rotation, the greater the demagnetizing force and the greater the distortion of the field.

When the action of motors is considered, it will be understood why the distortion of the field is in an opposite sense to that of a generator, but with the same cross-magnetizing and demagnetizing effects.

Interpoles.

Interpoles are magnetic poles that are placed between the main field poles of a generator or motor. The armature current is led around these poles in such a direction that the flux produced by it tends to reduce the distortion of the field. As this increases with increase of armature current, the current of the interpoles increases in a like degree and the distortion is, to a great extent, corrected. This eliminates the necessity of shifting the brushes on changes of load, and is especially efficient on motors whose speed is varied by field regulation. It is sufficient to state here that the speed of ordinary shunt motors becomes greater as the normal field flux is weakened. Without interpoles the weakening of the field to accomplish this necessitates shifting of the brushes to prevent injurious sparking, which in turn increases the demagnetizing effect and a condition might be reached when the armature flux would reverse the field flux over a portion of a main field pole and excessive sparking would occur and the motor would race to an unsafe speed. The interpole current reduces these armature reactions, and permits of greater range of speed without shifting of brushes and permits the commutation of the current to be effected without sparking.

The primary object of interpoles is to assist in the commutation, so that all sparking with its injurious heating effects may be avoided. If the brushes could be placed in a position where the voltage between adjacent commutator bars was a minimum and very small, there should be little sparking, but with high speed generators with small commutators this condition is difficult to obtain. In the case of high speed in motors caused by weakening the field, the voltage between commutator bars is comparatively high and commutation troubles are apt to occur. Perfect commutation requires the generation within the armature coil under commutation of an E. M. F. of the proper value and sign to reverse the current while it is still under the brush.

In Fig. 72 is shown the distribution of magnetic flux under the pole faces of a two-pole machine without interpoles both for light and full-load current. The curve for light load, shown by broken

line, shows a fairly uniform distribution of the flux over the whole pole face, and that for full load, shown by full line, shows the distortion due to the armature reactions above considered, the flux being dragged in the direction of rotation and being strong under one pole tip and weak under the other.

Considering the full-load curve, it is seen that the coil under brush B has E. M. F. induced in it which tends to keep the current flowing in the same direction as it does up to that point and with

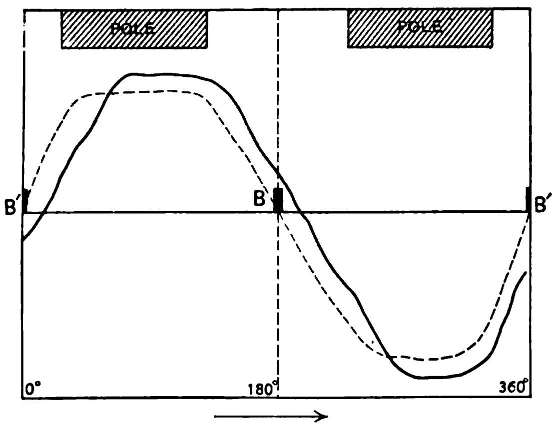


FIG. 72.—Distribution of Magnetic Flux without Interpoles.

the brush in this position commutation would be very imperfect and bad sparking would occur. The E. M. F. generated in this coil under the brush opposes what is intended to be done, *i. e.*, the reversal of the current before it leaves the brush. The field is such that the E. M. F. actually tends to generate more current in the same direction rather than to reverse it. In the above condition there is another effect acting against sparkless commutation. This is due to the lines of force around the coil under the brush which, as the currents tend to reverse, acts to prevent it, due to the self-induction of the coil. The local E. M. F. due to this self-induction causes the current to keep in its original direction and so opposes reversal.

Fig. 73 is drawn similar to Fig. 72 and shows the distribution of flux due to full-load current without interpoles in full and broken lines, and the flux due to the interpoles in dotted lines; with the resultant flux due to full-load current and interpoles in full line.

It will here be seen that the coil under brush *B* is passing through a flux that will generate an E. M. F. of oposite sign to that of the current to be reversed. This is of material help in causing reversal of the current, and the self-induction effect mentioned above is also

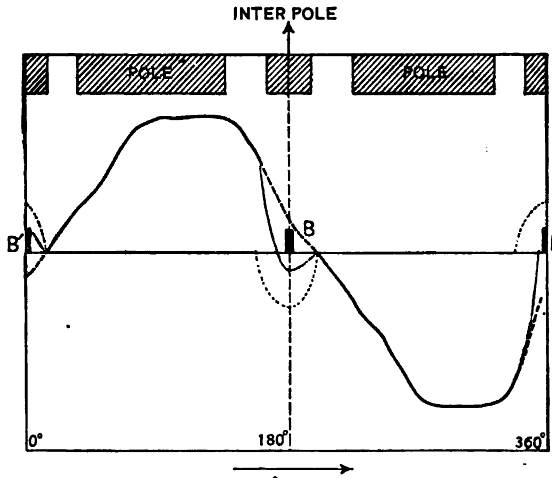


FIG. 73.—Distribution of Magnetic Flux with Interpoles.

reversed, both causes tending to good commutation. It will be noticed that as the flux due to the interpoles is caused by the armature current, this increases with the load, and if good commutation is effected for one load it should be expected at all loads without any change of brushes. In motors, as the speed is varied with constant load, the armature current changes, and consequently the interpole flux varies with the main field flux to such an extent that the whole arrangement is almost perfectly automatic.

As the interpole current is in series with the armature current, the reversal of one reverses the other, and in all cases of interpoles, the current flowing around them must be considered as armature current.

Interpoles are sometimes used on generators that are driven by turbines at a high rate of speed in order to suppress the sparking caused by the high frequency of commutation.

It is possible to get very close speed regulation on an interpole machine that is especially designed for this feature. In general, the speed regulation on an interpole motor can be made very small by giving the brushes a motor lead. A very slight movement causes a big change in speed and improves speed regulation. Care must be exercised, however, as a backward lead tends to make the motor unstable and when the load is put on it will "race." A backward motor lead in the case of a generator increases the compounding as does also too strong an interpole winding.

The interpole machine in general has the following characteristics.

1. Good commutation under all conditions of load.

2. Low commutator temperatures and long-lived commutators on account of this good commutation.

3. Excellent speed regulation as motors and voltage regulation as generators.

4. Ability to start quickly and to commutate under sudden and large change of load.

5. Less weight and flood space for a given output than in the case of a machine without interpoles.

6. Large variations in speed can be obtained, ratios from 5 to 1 are frequent.

Interpoles are more fully discussed under "Notes and Care of Motors," in Chap. II, Vol. II.

CHAPTER X.

GENERATORS.

A consideration of the elementary theory of the **generator** shows that in order to produce a continuous current in the external circuit, there must be (1) **a magnetic field,** (2) a collection of conductors called the **armature,** designed to revolve in the magnetic field, (3) an arrangement of conductors called the **commutator** for commuting the reversals of the current in the armature into one direction in the external circuit, and (4) an arrangement of conductors, called **brushes,** for making connection between the revolving armature and the external circuit.

The magnetic field may be produced by permanent magnets or by electromagnets, and in the latter case the current may be taken from some external source or from the current produced by the revolving armature itself. If the current is taken from the armature, all of the current may be used to produce the magnetic field, in which case the generator is called a **series** generator; or only a part of the current may be used, the generator then being called a **shunt** generator; or, again, a combination of these two methods may be used to energize the field magnets, in which case the generator is called a **compound** generator.

Separately Excited Generator.

In this form of generator, the magnetic field is produced by a current from a separate source of supply while the current due to the induction in the armature is lead off from the brushes to its external circuit. A typical form of separately excited generator is shown in Fig. 74.

Series Generator.

In this form of generator, the magnetic field is produced partly by the permanent residual magnetism of the poles, due to the metal

of which they are made, and to the current that is produced as a result of the induction in the conductors on the armature. The armature conductors are connected in series with the external circuit by means of the brushes and the whole current is lead around the field pieces. When this current flows around the metal field pieces, they become strongly magnetic, producing a strong magnetic field in the region in which the armature is made to revolve. The stronger the current the greater is the magnetic field, or at least up to the point of saturation of the field magnets. By this is meant

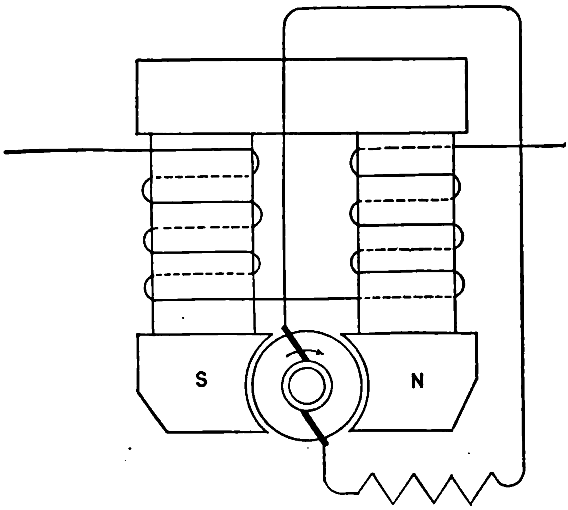


FIG. 74.—Separately Excited Generator.

the limit in the number of lines of force which the magnetic material is capable of producing. The number of times the series winding is carried around the field magnet spools, multiplied by the number of amperes flowing, is called the *ampere turns,* and the saturation of the magnetic material depends upon a given number of ampere turns, beyond which the magnetization will not increase, but will rather decrease.

Fig. 75 shows the typical form of series generator, showing the brushes, the field winding, the external circuit, and armature conductors all connected in series with one another.

In this form of generator, it is seen that no E. M. F. is generated in the armature as long as the external circuit is open, for then there is no current flowing around the field magnets. There may be a small E. M. F. generated due to the residual magnetism, but of course is not manifested as the circuit is not complete. In order then that this form of generator shall *build up,* that is produce a difference of potential at the brushes, the *external circuit*

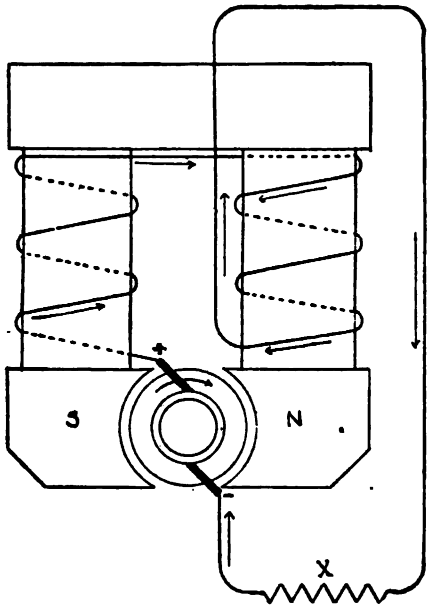


FIG. 75.—Series Generator.

must be completed, and the resistance must not be too high, or the small difference of potential, due to the residual magnetism, may not be sufficient to force current through it, and thus prevent any from flowing around the field magnets. Then, again, a series generator will not generate until a certain speed is reached. Any increase in the external resistance lessens its power to supply current, lessening as it does its ampere turns and consequently its effective magnetism. Any decrease in the external resistance, as

in adding lamps in parallel, has the effect of increasing the current, increasing the magnetization, and thus again the current, and a continued decrease in resistance might result in burning out the armature or the lamps. The series coils must carry the whole current so they must be of large wire to prevent overheating, and of only a few turns, for as the proper magnetization is proportional to the ampere turns, the latter may be obtained by a large current, as in this generator, and a small number of turns.

Regulation.—The E. M. F. of a series generator may be regulated at a given speed (1) *by controlling the current in the external circuit,* (2) *by cutting out part of the magnetizing coils,* and (3)

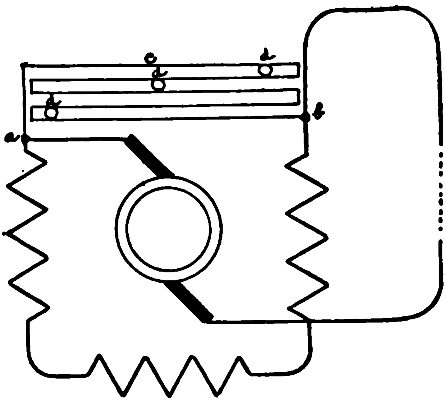


FIG. 76.—Series Shunt.

by sending part of the main current through a shunt to the series windings. The only one of these three that finds a practical use in the series windings as applied to a compound generator is the last and this should be understood, as it is the method used in the final compounding of compound generators.

In Fig. 76, *a* and *b* are the terminals for the series windings, and in addition to the series winding, these terminals are connected by a shunt circuit in which there is a variable resistance *c,* regulated by the short-circuiting plugs *d.* Part of the main current that would otherwise go around the series coils is shunted through this circuit, and by moving *d* the magnetizing current and consequently the E. M. F. at the brushes may be regulated.

Characteristic Curve.—The characteristic curve of a generator is a name given to a curve that may be plotted to show the relation between the number of volts generated in a generator and the resulting number of amperes, using volts as ordinates and amperes as abscissæ. The volts used may be the total volts and the amperes the total amperes, in which case the curve is called the *total* characteristic curve. In the case of the series generator, if the curve is plotted with the E. M. F. at the terminals and the external current, also in this case, the internal current, the curve is called the *external* characteristic curve. The *internal* characteristic of a series generator would be a straight line, the tangent of the angle this line makes with the current line being equal to the internal resistance.

The curve used in compounding generators is the external characteristic curve, but as they all show the interior workings of the generator under varying conditions a typical curve of each is shown with a mention of some of the facts that can be learned from them.

In Fig. 77 the line OE represents the total characteristic curve of a series generator for a given speed, the ordinates being volts and the abscissæ amperes, being plotted from the total E. M. F. generated and the resulting external current. This curve starts a little distance above the zero line, showing a certain amount of residual magnetism. The curve ascends first at a steep angle, then curves around and again assumes nearly a straight course. In this generator the magnetization increases with the current, and so the E.M.F. increases rapidly at first, giving the straight portion of the curve. As the current increases, the magnets approach saturation, so any increase in current does not produce a corresponding increase in E. M. F. and this is shown by the curving or flattening for a short space in the curve. If a still further increase takes place, armature reactions, demagnetizing, and cross magnetizing effects take place, and a shifting of the brushes due to the increased current causes a marked demagnetizing effect and in some generators causing a decided drop in the curve. This curve shows at what point saturation commences to be manifested, when it has really reached the saturation point, and the current necessary to produce the maximum E. M. F., or rather the current produced by the maximum E. M. F. and at what time the most serious of the arma-

ture reactions take place. It also shows at what current, or the limits of current, the total E. M. F. is most nearly constant.

The curve *Oe* is plotted for the total current and the difference of potential at the brushes or terminals. The difference in the ordinates of the total and external characteristics show the volts that are lost in overcoming the internal resistance, that of the armature and series windings, and from being useless as far as

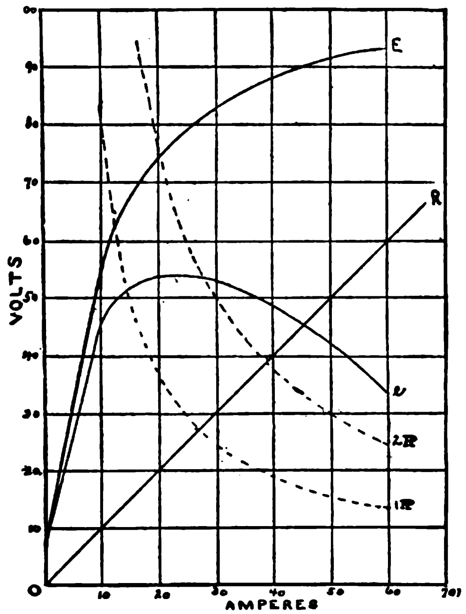


FIG. 77.—Characteristic Curves of Series Generator.

external electrical energy is concerned are called "*lost volts.*" This curve shows between what limits of the external current the difference of potential at the terminals is most nearly constant, consequently at what load the machine could be used with the least variation in E. M. F.

The full straight line *OR* is the curve of internal characteristic, and its ordinate at any point represents the "lost volts" for the corresponding current, and is equal to that current multiplied by

the sum of the armature and series winding resistances. This curve then represents the difference between the other two, and having either two, the remaining one may be plotted. As the internal resistance is known, the internal characteristic may be easily plotted, and the data for the external characteristic may be obtained by properly connecting an ammeter in circuit and attaching a voltmeter to the terminals. Then by adding to the ordinates of the external characteristic the ordinates of the internal for the same current, the total curve can be plotted.

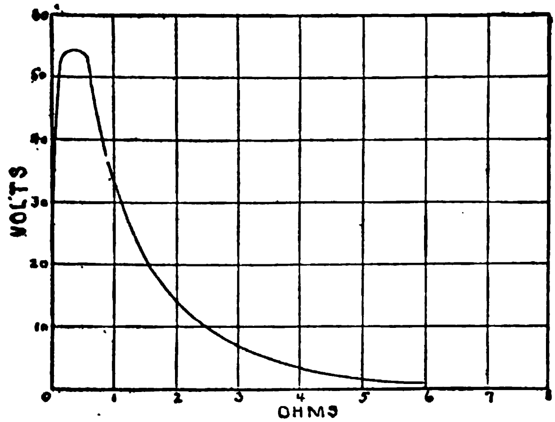


FIG. 78.—Curve Showing External Resistance and Terminal Voltage, Series Generator.

Horse-Power Lines.

Another interesting fact in connection with these curves is that they can be made to show the horse-power which is being developed at any particular part of the circuit. These horse-power lines constitute a system of rectangular hyperbolæ, the axes of volts and amperes being the respective asymptotes. That is $xy = a$ constant, x being volts and y amperes. The one horse-power line should be the locus of all the points such that the product of the ordinate and abscissæ of every point is equal to 746 watts. Thus one point would be 74.6 volts and 10 amperes, another 37.3 volts and 20 amperes, and so on. The two horse-power line should be a result

such that the product of ordinate and abscissæ at every point should be 2×746 watts.

An examination of the resistance curve or line shows that, if the resistance is above a certain value, the angle it makes with the ampere line being greater than the angle made by the slope of the total characteristic curve, the machine cannot build up; and it also shows that while running, if from any cause the resistance is suddenly increased, the machine will rapidly unbuild or lose its magnetism, that is, the ordinate of the resistance becomes negative as applied to the external curve. These curves explain a great many things in connection with the running of generators that were known before simply as facts.

Another interesting curve useful in compounding generators is a curve showing the relation between the external resistance and the difference of potential at the terminals. A typical curve is shown in Fig. 78, but its application will be deferred until compound generators are considered.

Shunt Generators.

In this generator, the magnetic field is produced partly by the permanent residual magnetism of the field pieces and by a shunt current that is led off from the terminals of the machine. As the current in the shunt field, as it is called, is lost as far as any external electrical energy is concerned, it is sometimes called the "*lost amperes.*" As this loss should be as little as possible, in well-designed machines not more than 5 per cent of the armature current passing through the fields, the resistance must be high, and in order to produce the proper number of ampere turns, the number of turns must be very great, so the shunt winding usually consists of a very great number of turns of fine wire.

Fig. 79 shows the typical form of shunt generator, the shunt current being taken off from the brushes around the pole pieces, the main current being taken off from the brushes through the external resistance R.

This machine will not build up if the external circuit is closed, for then all the current generated would tend to take that path on account of its resistance being so much smaller than that of

the shunt windings. If the external circuit is open, and the armature made to revolve, owing to the small amount of residual magnetism in the pole pieces, there will be generated a small difference of potential at the brushes, and this difference of potential will cause a small current in the shunt windings, which will in turn, increase the magnetization, this increasing the E. M. F. at the brushes, and so the machine gradually builds up to full voltage,

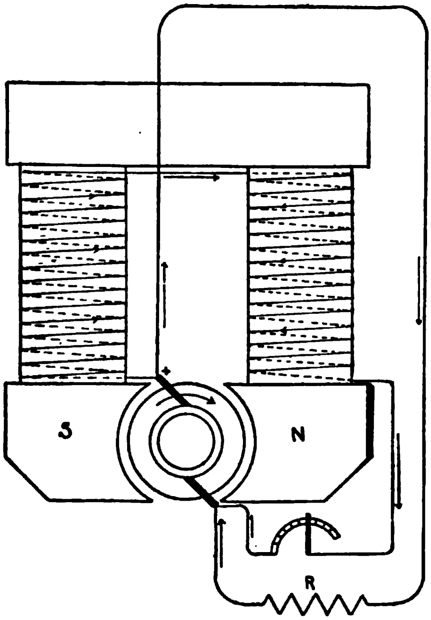


FIG. 79.—Shunt Generator.

attaining its full value when no current is flowing in the external circuit, and all the armature current is in series with the shunt current. When an external current flows due to closing the external circuit, the difference of potential at the brushes gradually falls, on account of the internal resistance of the armature conductors and of the reactions of the current on the field. A greater proportion of the whole current follows the external path, thereby lowering the E. M. F. at the brushes, and consequently reducing the

shunt current, which decreases the magnetization, and which reacts to still lower the E. M. F., so as the external resistance gradually falls, the total current may increase for the time, but a less proportion flows around the field, and the voltage falls, and if a certain low external resistance is reached, the machine will rapidly unbuild and the voltage and current fall together to zero.

Regulation.—In order to compensate for the decrease in the E. M. F. when load is thrown on a shunt generator, a rheostat of comparatively high resistance is placed in series with the shunt winding, and so adjusted that when no external current is flowing only enough current flows through the field to produce the proper E. M. F., and this is kept constant by throwing out some of the resistance as the load increases, so that the shunt circuit will have an increasing or rather a steady instead of a decreasing current, thereby maintaining a constant magnetization and constant E. M. F.

Characteristic Curves of Shunt Generators.—There are five curves that show relations existing between the volts and amperes in a shunt generator, one internal characteristic and four external curves. The internal curve, plotted with the total volts and the total current when the external circuit is open is very similar to the total characteristic curve of the series generator. When the external circuit is closed, there are four variable quantities, namely, the total E. M. F., the E. M. F. at the brushes or terminals, the armature or total current, and the external current. Calling the total E. M. F. *E*, the E. M. F. at the terminals *e*, the total current *Ca*, and the external circuit *C*, four curves can be plotted, *e* and *C*, *e* and *Ca*, *E* and *C*, *E* and *Ca*. Of these *e* and *C* is the one principally concerned in the compounding of generators, though all are of interest and are shown in Fig. 80.

Curve No. 1 is plotted from *e* and *C*, No. 2 from *e* and *Ca*, No. 3 from *E* and *C*, and No. 4 from *E* and *Ca*. *OA* is drawn at such a slope that the tangent of the angle it makes with the ampere axis represents the resistance of the armature, and *OS* at such a slope that the tangent of its angle represents the resistance of the shunt winding.

If curve 4, obtained with the total E. M. F. and the total current, is plotted, the others may all be obtained from it. Curve 2

is obtained from 4, by subtracting from the ordinates lengths which are included between OA and OC. Thus the point 2 is obtained by subtracting the distance CF from $C4$. The distance CF represents the "lost volts" for the current OC corresponding to the E. M. F. $C4$, and similarly the ordinates represent the lost volts for any corresponding armature current.

Curve 3 is obtained from 4 by subtracting the abscissæ lengths which are included between OS and OD. Thus the point 3 is obtained by subtracting the distance XY from $D4$. The distance

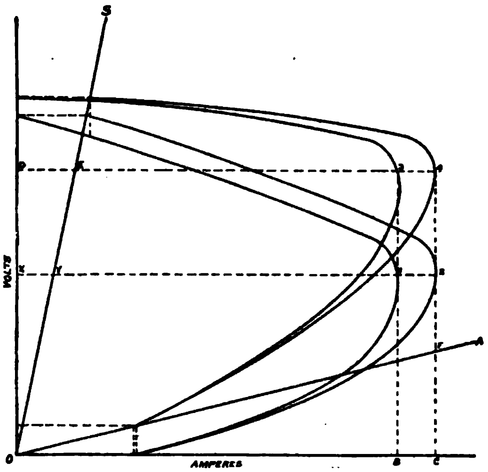


FIG. 80.—Characteristic Curves of a Shunt Generator.

XY represents the amperes in the shunt circuits, or the "*lost amperes*" for the difference of potential $C2$, and similarly the abscissæ between OS and OD represent the lost amperes for any corresponding difference of potential.

Curve 1 is obtained by taking the ordinates (lost volts) from curve 3 and the abscissæ (lost amperes) from curve 2 corresponding to any point on curve 4.

In practice, it is more usual to plot curve 1, by observing the difference of potential at the terminals with a voltmeter and measuring the external current with an ammeter. Curves 2 and 3 can then be drawn, and from these two, curve 4 can be plotted.

These four curves are curiously different from that of the series generator. The volts are a maximum when the external circuit is open, and as the external current gradually increases, the difference of potential gradually falls, due to the fact that a smaller proportion of the total current is now flowing around the field magnets. At first this fall is gradual, but at a certain current the curve rapidly turns and then descends rapidly towards the origin in a nearly straight line. This shows why a shunt generator will not build up if the external circuit is closed, and how it rapidly unbuilds if the external resistance is lowered to a certain amount. The straight

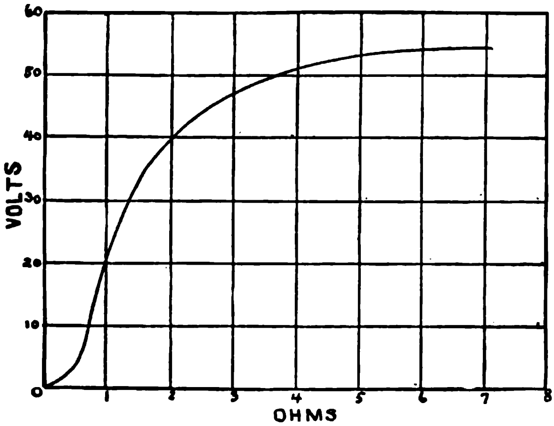


FIG. 81.—Curve Showing External Resistance and Terminal Voltage, Shunt Generator.

portion shows the critical state, and shows that if the external resistance is altered the slightest degree, both the volts and amperes alter to a very great degree.

These curves show that the shunt generator will only work if the resistance of the external circuit is greater than a certain value, while the series generator will only work if the resistance is less than a certain value.

A curve (Fig. 81) showing the relation between the volts and resistance is instructive, as by its combination with the corresponding curve of the series generator the curve for the compound generator is made.

Compound Generators.

Having now seen the principles upon which the series and shunt generators are built, we are in a position to take up the compound generator, which is simply a combination designed to produce a constant difference of potential at the terminals irrespective of the external current or resistance. A compound generator can then best be considered as a shunt generator, upon which there is also wound a few turns of series windings. Under the curve for the shunt generator it was seen that as the external current was increased, or what amounts to the same thing the external resistance

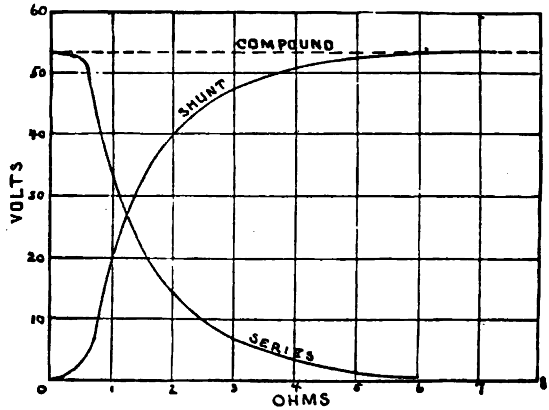


FIG. 82.—Curve of Compound Generator.

decreased, the difference of potential gradually fell and in the series curve, the difference of potential gradually increased under the same circumstances. So by combining these two curves, a curve of constant potential or a straight line might be produced, and that is the sole object of the compound generator. This could be well represented by combining the two external curves of the series and shunt generators, but is still better shown by combining the two curves plotted with volts and ohms, for each generator as shown under the respective heads of series and shunt generators. These curves are shown in the figure.

The shunt curve in Fig. 82 shows what was seen before, that the greatest E. M. F. occurs when the external resistance is greatest,

or when the external circuit is open, and as the resistance is gradually decreased, or the external current gradually increased the E. M. F. gradually fell. The opposite takes place in the series generator, for when the resistance is high scarcely any current flows around the field spools, and there is practically no E. M. F., but as the resistances decreases, or current increases, the E. M. F. gradually rises. If there is a proper relation between the resistances of the two windings, one will raise the E. M. F. just as much as the other lowers, so the sum of their ordinates at any point will be constant, and the compound characteristic is represented by the dotted straight line, marked compound.

In the type of compound generator used in the navy, in addition to the fixed shunt and series windings, there is a regulator introduced in the shunt field as explained under the shunt generator, and a shunt to the series winding as explained under the series generator. This latter is adjusted when the machine is being compounded, and when once adjusted to give the proper difference of potential should not thereafter be tampered with, but any variations in the E. M. F. should be regulated by the shunt field **rheostat**.

The Building Up of a Generator at Starting.

When a self-excited generator is started, there is a small E. M. F. induced in the armature coils due to the magnetic field produced by the small residual magnetism. This small E. M. F. produces a current which, flowing around the magnets, *strengthens* the field, which in turn induces higher E. M. F.; this produces greater current which still more strengthens the field and so on until the machine is built up to full voltage. This operation is called **building up**, and there can be no building up unless there is some residual magnetism. If the field magnets show no residual magnetism whatever, the field circuit should be connected with some outside source of current, either a few cells of a storage battery or the current from a running machine.

If the connections of the field are such that the induced current tends to *weaken* the residual magnetism, then the machine cannot build up at all. With a given direction of rotation of the armature and a certain polarity, the induced current tends to go in a certain

direction. If now the connections are such that the induced current due to the residual magnetism weakens it, the current will also weaken. If the current was strong enough to reverse the polarity of the field magnets, then the induced currents would flow in the opposite direction and would be again acting to weaken the field.

With a given direction of armature rotation and given field connection, a generator does build up; it cannot build up, if its direction of rotation be reversed, or if its field connection is reversed; but it will build up, however, if both the direction of rotation and field connections are reversed at the same time.

If a generator does not build up, it may do so by changing either the direction of rotation of the armature or by changing the field connections.

Comparison of Terminal Voltage in Different Generators.

The field current of a separately excited generator can be kept constant, so that the armature flux is practically constant except for the demagnetizing effect of the armature when delivering its current.

Separately Excited Generator.—As the current rises, due to a lessening of the external resistance, the drop of potential in the armature, $C_a r_a$, increases, so the terminal voltage decreases with an increase of current, and also slightly due to the increased demagnetizing effect when the current increases.

The terminal voltage falls off as the speed decreases, as the total E. M. F. depends on the speed and flux, as seen from the fundamental equation, and the total and terminal voltages vary almost in proportion with the speed.

Series Generator.—The total E. M. F. is proportional to the speed and for any given external current, the terminal voltage varies directly with the total E. M. F. and with the speed.

The voltage is zero when the current is zero and increases rapidly with the external current, the lost volts increasing with increase of current. With a certain speed, the terminal voltage falls off as the external resistance is decreased.

Shunt Generator.—A decrease of speed in a shunt generator

causes a decrease in both the total and terminal voltages, and the lessening of the terminal voltage decreases the field current and consequently the magnetism, so the voltages fall more in proportion than in a separately excited machine.

An increase in the external current causes a greater decrease in the terminal voltage than in a separately excited generator, because on account of the increased armature current, the drop is greater, and consequently the terminal voltage is less, and also the field excitation is less.

Compound Generator.—The field excitation of a compound generator is increased by an increase in the external current due to the series windings. If the series winding has enough coils, it may counterbalance the demagnetizing action due to the increased current and the drop in the terminal voltage due to the shunt winding and may increase the total E. M. F.

If the series coils are made of just enough turns to counteract the drop in the armature and field due to the increased current, $C_a r_a + C_a r_m$, the terminal voltage may be kept approximately constant.

If the series windings has the effect of increasing the total E. M. F., that is, if it more than compensates for the drop, the terminal voltage will increase with increase of current, and the machine is said to be **over compounded.**

Over Compounding.

By proper adjustment of speed and resistances, machines can be made to give a constant difference of potential for a certain range of external current which may not be constant over the entire limit of external current. A machine is said to be over compounded when the difference of potential at the terminals is higher than the E. M. F. at some point in the circuit over which the E. M. F. is to be constant for the range of current used. It is usually due to a preponderance of the series winding over the shunt. There is no necessity of over compounding generators on board ship for the leads are short and their resistances low. It is, however, absolutely essential to know over just what range of external current the E. M. F. is constant. Thus, of two machines built entirely

alike of 100-amperes capacity, one might have an absolutely constant E. M. F. from 0 to 50 amperes, and not so constant for the rest of the load, while the other might be not quite so constant in the first half of its range, but entirely constant in its second half. In running these machines in parallel, they would only automatically work so to speak, over the range of current common to both in which the E. M. F. was constant, though of course they could be regulated so as to divide their loads equally by adjusting the shunt rheostats.

Uses of Different Classes of Generators.

Separately excited generators are used mostly for testing where a constant E. M. F. is desired or where changes of speed affect but slightly the terminal voltage.

Generators used for charging storage batteries are usually separately excited, as they are working against an opposing E. M. F. which would act back through the generator if it was not immediately disconnected on stopping. Separately excited generators are much less likely to have the field magnetism reversed. They are also used largely for electroplating.

Series generators cannot be used where constant voltage is desired, but can be used for supplying constant current at varying voltages, the voltage being regulated by devices to keep the current constant on changes of the external resistance.

Shunt or compound generators are used for delivering varying current at constant voltage, as in electric lighting and in most forms of power. They are driven at or near constant speed by the motive power available.

The fields of alternating current generators are separately excited, as a steady field could not be produced by the alternating current of the armature.

CHAPTER XI.

EFFICIENCIES AND LOSSES OF GENERATORS.

Efficiency as applied to a generating set, that is, a generator and the power that drives it, is a term used in more than one sense, and to intelligently understand what is meant, the definitions of the terms ordinarily used will be given, and reasons given for the existing differences.

Gross Efficiency.

On board ship, the generators are directly connected to the shaft of the driving engine, either by means of a solid shaft or by a clutch bearing. All of the power developed by the engine and applied to the armature is not converted into electrical energy in the generator, and the gross efficiency is a term applied to express the relation between the *gross power actually applied to the armature shaft* and the *gross electrical power converted in the armature.* One of these is mechanical power, the other electrical, and to obtain the percentage efficiency, they must both be expressed in the same units, either both electrical or both mechanical.

The total power applied to the shaft is ordinarily obtained by taking indicator cards of the engine while running at the standard speed. The total electrical power converted can best be determined by calculation; by measuring the total external current and the difference of potential at the terminals, and from these quantities, by means of the dynamo equations, find the total E. M. F. and the armature current. Their product divided by 746 will give the horse-power actually converted, and the percentage of the total horse-power that this represents will be the gross efficiency. It must be noted that in expressing the gross efficiency, it is necessary to state under what conditions of external load the generator is running, for the total power converted depends upon this quantity and hence does the efficiency.

Electrical Efficiency.

This is a term given to express the relation between quantities that are entirely electrical, and might be considered the efficiency of the generator itself. It is the relation between the *total power actually converted in the generator* and the *net output, or the electrical energy available at the terminals.* The output is measured by a voltmeter and ammeter properly connected with the generator running at its rated speed, and with the load for which the efficiency is desired. With these quantities the total E. M. F. and the total armature current are obtained as in the case under gross efficiency. The product of the total E. M. F. and armature current gives the total number of watts converted, and the product of the difference of potential at the terminals and the external current gives the number of watts available for useful work, and the relation between these two quantities expresses the electrical efficiency.

Commercial Efficiency.

This is a term given to express the relation between the *total power applied to the shaft of the generator and the total electrical energy available at the terminals,* and as has been seen, must be the product of the other two efficiencies, the gross and electrical. This is the real measure of the efficiency of the generating set, and represents the relation between the power that is put in the set, the *input,* and the power that is taken out, the *output.* If the other two efficiencies are high, of course the commercial efficiency will be high also, though lower than either one. The quantities concerned are directly measured, one by the indicator cards of the engine, the other by voltmeter and ammeter; and the resulting efficiency is the one required by the standard specifications, full load on the generator being the standard load.

Losses.

Losses in generators are of two kinds, *electrical* and *mechanical,* and on their values depend the various efficiencies. The losses which represent the difference between the total power applied to the armature shaft and the total power converted in the armature

are partly mechanical and partly electrical, being losses in friction at the bearings, friction at the brushes, between them and the commutator, air friction of the revolving armature, eddy currents in the pole pieces of the magnetic field and in the conductors on the armature, and in the armature core, and a hysteresis loss in the armature core due to the armature revolving in a magnetic field. All of these losses are manifested in the form of heat which is dissipated into the air or tends to heat the parts involved and, being brought into existence by the power supplied, represents so much waste energy.

Of these losses, the friction losses are small and can be reduced by proper mechanical means. The loss due to the eddy currents induced in the pole pieces is also small, especially in forms of armature that are not slotted. These eddy currents are induced in and circulate round the pole pieces, being due to the relative motion of the lines of force and the iron masses, the field being apparently dragged along by the revolving armature, and the magnetic circuit being broken as the tip of the pole is left. These eddy currents can be reduced to a certain extent by laminating the pole pieces, and by increasing the size of the pole tip on the leaving horn of the pole piece, and cutting it away under the entering horn; the last arrangement also reducing the demagnetizing and cross magnetizing effect. The eddy currents tend to heat the iron masses, and this heat represents so much lost energy.

Loss due to eddy currents set up in the armature conductors themselves is very small indeed and could only be appreciable, if at all, in armatures having heavy solid bars as conductors, but could have no effect in armatures where the conductors are made up of stranded small wires.

The principal loss in power that is not converted into electrical energy in the armature is that due to hysteresis which is due to the reversals of the magnetic field and its reaction on the iron masses of the armature core. *Hysteresis* is the name given to express the magnetic lagging of effects behind the causes which produce them. If the magnetism be rapidly reversed in a magnetic substance, there is a lagging of the field behind the cause of the reversal and to this phenomenon the name hysteresis has been given. The rapid

reversal of a magnetic field will produce heat in the magnetic substance, which is a loss from the power which produces the change. The revolution of the generator armature in a magnetic field has the effect of reversing the magnetic field; the same effect, in fact, as though the armature was at rest and the field was actually reversed. Laminating the iron core of the armature has the effect of reducing eddy currents and a consequent loss due to heat they produce, but it does not affect the hysteresis loss, as that depends only on *the magnetic substance of the core,* on *the flux density* of the magnetic field, and on the *number of reversals* of the field; this last depending on the speed and number of poles.

The loss due to hysteresis is reduced by using as armature discs soft annealed metal that does not show much residual magnetism, and this is effected by using a metal approaching pure iron, having little of the steel characteristics.

The loss in armatures due to eddy currents and hysteresis may be separated, as the eddy currents are true electrical currents, and their heat waste varies as the square of the current, and the hysteresis loss only as the current.

The difference between the power actually converted in the armature and the electrical output of the generator is represented by the losses which take place in the conductors of the generator itself; that is, in the armature conductors and in the conductors that make up the series and shunt windings. The losses in the windings of the field are designated **field losses,** and those in the armature, **armature losses,** to distinguish them from the losses in the armature core, which are sometimes called **core losses.**

In a compound generator there are two field losses, that due to the series windings and that due to the shunt windings. When the generator is giving out its rated E. M. F., the shunt loss is constant as the current is constant to produce the constant magnetization, and the resistance being unchanged. The loss then expressed in joules would be $C^2{}_s r_s t$. It must be borne in mind, however, that if there is a regulator in series with the shunt field, loss due to its resistance must be added to the other, in joules being $C^2{}_s rt$ (regulator). The loss in the series windings depends on the external load, the series current varying with the armature current

at any time, its loss in joules being $C^2{}_m r_m t$. The armature loss depends on the external load, and at any time would be $C^2{}_a r_a t$ joules. All these expressions show that the smaller the resistances, the smaller the losses—and the ideal generator would be one of infinitely small resistance. These are all heat losses, the effect of which is to heat the conductors through which the currents flow, and unless some means is taken to allow the heat formed to be radiated off, this heat forms a serious drawback, independent of the loss of electrical energy. The series coils are usually in the form of ribbon, for the double purpose of allowing greater radiating surface and for the ease with which they can be wound on the magnet spools.

These losses can be considered in another sense, that of the power used to force the currents through the several resistances. For instance, in the case of a long-shunt compound-wound generator, the difference of potential at the terminals being e, the power in watts expended in forcing the current through the shunt winding would be eC_s. That lost in forcing the current through the series windings would be $(e' - e)C_m$, and that lost in the armature $(E - e')C$.

From the dynamo equations, Chapter XII,

$$e = C_s r_s,$$

or

$$eC_s = C^2{}_s r_s$$

$$e' - e = C_a r_m$$

$$(e' - e)C_m = C^2{}_m r_m.$$

In the long shunt

$$C_a = C_m$$

and

$$(E - e') = C_a r_a$$

$$(E - e')C_a = C^2{}_a r_a.$$

Multiplying these by t, expresses the watts lost as joules.

The total power converted in the armature is the product of the total E. M. F. and the total armature current or EC_a; the total available power is the product of the difference of potential at the terminals and the total external current or eC. The difference of these two must represent the total copper losses, or in the long shunt compound generator,

$$EC_a - eC = C^2{}_s r_s + C^2{}_a r_m + C^2{}_a r_a.$$

The total available power in the external circuit is C^2R, or

$$EC_a = C^2R + C^2{}_s r_s + C^2{}_a r_m + C^2{}_a r_a.$$

$$\therefore \qquad eC = C^2R,$$

which is of course true as

$$e = CR.$$

The expression for the electrical efficiency would be

$$\text{Efficiency} = \frac{eC}{EC_a};$$

or, as given under dynamo equations,

$$\text{Efficiency} = \frac{C^2R}{C^2R + C^2{}_s r_s + C^2{}_a r_m + C^2{}_a r_a}.$$

Limit of Output.

In the case of a generator designed to give a constant difference of potential at the terminals, the amount of current flowing through the armature depends on the external resistance. As this resistance is reduced by adding incandescent lamps in parallel, it becomes a matter of importance to know how far this resistance may be lowered; or, in other words, how much current can be safely taken from the generator. In a given generator the calculations are based on a given maximum current, and the conductors of the armature are calculated to safely withstand this current; but the question is, what limits the current and what should be the basis of the calculation? We have seen under *losses* that the internal losses in the generator are all in the nature of heat losses, the number of joules lost in a given time being C^2rt, for the part of the circuit under consideration.

Heat.—The heat formed by the currents tends to dissipate itself into the surrounding air, but if the heat is produced by the current faster than it is radiated, it is very evident that the parts themselves will be heated. If the generator is at rest and has been for some time, all of its parts will attain the temperature of the air; if now the generator is started with an external current, heat is formed in the conductors, and if it is radiated as fast as produced there will be no rise in temperature. This is seldom the case, however, and the

temperature of the parts will go on slowly rising. The greater the current taken from the generator, the greater will be the increase in temperature for the same time. Now it is very evident that one limit of the amount of current is the temperature limit due to that current. At a certain temperature the materials used in the insulation of the conductors and the different windings of the generator, such as paper, cotton, silk, etc., will char and disintegrate to such an extent as to be worthless for what they were designed. For a short time they may stand a temperature somewhat higher than the charring temperature, but if submitted for any length of time to a temperature of 180° F., they will quickly break down. Consequently, no current should ever be taken from a generator such that the heat formed should raise its temperature to 180° F.

If the temperature of the air is as high as 180° F., it is very evident that the machine should not be run at all, for all parts will be at that temperature, and there could be no allowable rise in temperature, due to the generator currents, so in stating the allowable rise, it is very necessary that it should be a rise in temperature above that of the surrounding air. If the machine could be kept in a room at the freezing point, and the heat imparted to the air so carried away that it would remain at the freezing point, the allowable rise due to the current would be 180° — 32°, and from this generator under those conditions, a greater current could be safely carried than at any initial higher temperature.

The specifications for generators used in the service state that after a four-hours' full-load trial, no part of the machine shall be allowed to be higher than 40° C., greater than the temperature of the room; or, in other words, the temperature due to the armature current shall not be greater than 40° C., above the temperature of the air. The average temperature of the air is to be taken as 25° C.

Sparking.—Besides the limit of temperature which limits the amount of current that can be safely carried, there is another consideration that will be lightly touched on. As the current from the armature increases, the magnetic field of the armature core increases and the magnetic field of the field pieces remaining constant, certain reactions take place between these two fields. These reactions

have a tendency both to cross magnetize and to demagnetize, one effect of which is to necessitate the shifting ahead of the brushes from their normal positions. The brushes should ordinarily be placed in the neutral part of the field, that is, where the induction in the armature coils is a minimum, and in this position there will be little or no sparking. If the current is increased, greater reactions take place, necessitating further movement of the brushes to reduce sparking, but this movement of the brushes produces further change in the magnetic reactions, and if the current is strong enough the armature field may be powerful enough to overcome the field, and there can be no position found in which the brushes will have no sparking. This sparking of course is very injurious, and when heavy, rapidly wears away the brushes and the commutator segments, rapidly pitting and scarring them, and the heat due to the sparking may be great enough to fuse two or more adjacent segments, thereby short-circuiting their coils, and soon burning them out. This sparking can be reduced by good preliminary design; by making the field magnets relatively very powerful in relation to the armature field, but still in any given generator, a current in excess of the designed amount may produce injurious sparking, so this may well limit the amount of current that may safely be taken from any machine.

CHAPTER XII.

DYNAMO EQUATIONS.

In order to know just what is taking place in a generator when it is running at any certain speed with a given load in the external circuit, the dynamo tender should have a knowledge of the simple equations connecting the electromotive forces, currents, and resistances of the various parts of the field windings, armature, and external circuit. These follow directly from a consideration of Ohm's law and the laws of divided circuits previously given. These equations will enable one to calculate just what any particular generator is capable of doing, and are needed in order that the several efficiencies may be calculated under any given conditions. Of course they are used when the generator is under design, but with which this is not concerned. Examples will later be given to show their application.

The following notation will be used consistently throughout both with generators now and motors later:

E = total E. M. F. generated by generator or motor,
e = difference of potential at the terminals,
e' = difference of potential at the brushes,
$\mathfrak{E}$ = difference of potential at the motor terminals,
C_a = armature current,
C_s = shunt current,
C_m = series current,
C = external current,
r_a = armature resistance,
r_s = shunt resistance,
r_m = series resistance,
R = external resistance.

Series Generator.

In the series generator, there is but one circuit (Fig. 83), so $C = C_a = C_m$.

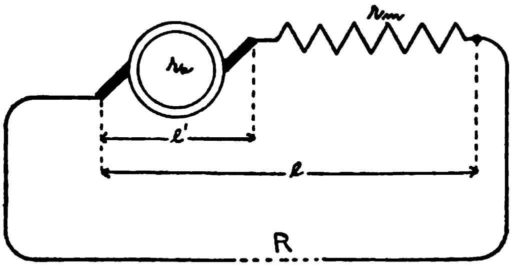


FIG. 83.—Series Connections.

By Ohm's law:

The fall of potential around the whole circuit $E = C(R + r_a + r_m)$,
" " " from terminal to terminal $e = CR$,
" " " " brush to brush $e' = C(R + r_m)$,
" " " through series windings $e' - e = Cr_m$,
" " " " armature $E - e' = Cr_a$.
Useful work in external circuit $= Cet \qquad = C^2Rt$ joules.
Total work in circuit $= CE \qquad = C^2(R + r_a + r_m)t$ joules.

Electrical efficiency $= \dfrac{\text{Useful work}}{\text{Total work}} = \dfrac{C^2Rt}{C^2(R + r_a + r_m)t} = \dfrac{e}{E}$.

The expression for efficiency shows that it is a maximum when both r_a and r_m are very small.

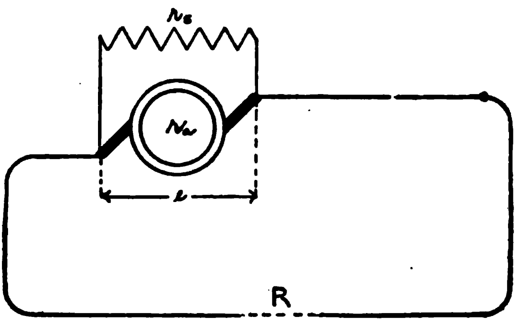


FIG. 84.—Shunt Connections.

Shunt Generator.

In the shunt generator (Fig. 84) there are three currents, one through the shunt windings, one through the external circuit, and one through the armature, the latter being equal to the sum of the other two. In this case the terminals and brushes coincide.

Total resistance outside of armature $= \dfrac{Rr_s}{R + r_s}$.

The fall of potential around the whole circuit $E = C_a\left(r_a + \dfrac{Rr_s}{R + r_s}\right)$,

" " " from terminal to terminal $e = CR$,

" " " from terminal to terminal $e = C_s r_s$,

" " " through armature $E - e = C_a r_a$,

or $E = e + (C + C_s)\, r_a$

$$C = \frac{e}{R} \qquad C_s = \frac{e}{r_s},$$

or

$$E = e + \left(\frac{e}{R} + \frac{e}{r_s}\right) r_a = e\left(\frac{Rr_s + Rr_a + r_a r_s}{Rr_s}\right),$$

or

$$E = er_a\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right),$$

an expression which allows E to be computed, by the several resistances being known and e measured at the brushes by a voltmeter.

Useful work in external circuit $= C^2Rt$ joules,
Work spent in shunt field $= C^2_s r_s t$ "
Work spent in armature $= C^2_a r_a t$ "

or

Electrical efficiency $= \dfrac{C^2R}{C^2R + C^2_s r_s + C^2_a r_a}$.

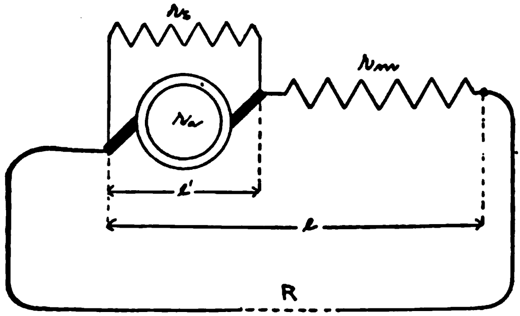


FIG. 85.—Short Shunt Compound Connections.

Compound Generator.

There are two cases in the compound generator, depending on whether the shunt current shunts only the brushes as shown in Fig. 85, or shunts both the armature and series windings as shown in Fig. 86. The former is called a **short shunt** compound generator and the latter a **long shunt** compound wound.

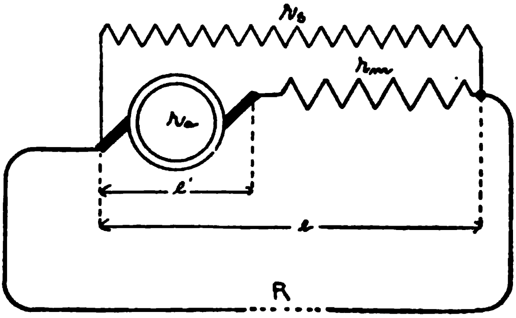


FIG. 86.—Long Shunt Compound Connections.

Short Shunt.

The fall of potential around the whole circuit $E = C_a\left(r_a + \frac{(R + r_m)\, r_s}{R + r_m + r_s}\right)$,

" " " from brush to brush $e' = C_s r_s$,

" " " from brush to brush $e' = Cr_m + CR$,

" " " " terminal to terminal $e = CR$,

" " " through armature $E - e' = C_a r_a$,

" " " through series windings $e' - e = Cr_m$.

Lost volts $E - e = C_a r_a + Cr_m$.

From the above expressions follows an equation by which the total E. M. F. may be calculated, knowing by measurement the difference of potential at the terminals and the value of the several resistances.

$$E = \frac{e(r_m r_s + Rr_s + r_a r_s + r_a r_m + Rr_a)}{Rr_s}.$$

Useful work in external circuit $= C^2Rt$ joules,

Work spent in shunt field $= C^2_s r_s t$ "

" " " series " $= C^2 r_m t$ "

" " " armature $= C^2_a r_a t$ "

or

Electrical efficiency $= \frac{C^2R}{C^2R + C^2_s r_s + C^2 r_m + C^2_a r_a}.$

Long Shunt.

The fall of potential around the whole circuit $E = C_a\left[r_a + r_m + \left(\frac{Rr_s}{R + r_s}\right)\right]$,

" " " from brush to brush $e' = C_a r_m + CR$,

" " " from terminal to terminal $e = CR$,

" " " from terminal to terminal $e = C_s r_s$,

" " " through armature $E - e' = C_a r_a$,

" " " " series windings $e' - e = C_a r_m$.

Lost volts $E - e = C_a r_a + C_a r_m$.

A similar expression, as in the case of the short shunt compound, may be deduced,

$$E = \frac{e(r_m r_s + Rr_s + r_a r_s + Rr_m + Rr_a)}{Rr_s},$$

the only difference being in the next to the last term.

Useful work in external circuit $= C^2Rt$ joules,

Work spent in shunt field $= C^2_s r_s t$ "

" " series " $= C^2_a r_m t$ "

" " armature $= C^2_a r_a t$ "

or

Electrical efficiency $= \frac{C^2R}{C^2R + C^2_s r_s + C^2_a r_m + C^2_a r_a}$.

Problems on Generators.

1. If a shunt wound generator has an E. M. F. of 108 volts at the terminals, resistance of armature .05 ohm, field coil 18 ohms, and outside mains .2 ohm, how many incandescent lamps can be lighted if each takes .75 ampere and has a hot resistance of 130 ohms? Find the total electrical energy and the energy in the lamp circuit in watts. If the net efficiency is 82 per cent, how many H. P. must be applied to the armature?

$x =$ No. of lamps $\quad C = \frac{e}{R} = \frac{108}{.2 + \frac{130}{x}} \quad C = .75x,$

or $\quad .75x = \frac{108 \times 10x}{2x + 1300} \quad$ or $x = 70$

$E = e + C_a r_a \quad C_a = C + C_s \quad C_s = \frac{e}{r_s} = \frac{108}{18} = 6$

$C_a = .75 \times 70 + 6 = 58.5.$

$\therefore \quad E = 108 + 58.5 \times .05 = 110.93$ volts.

Total electrical energy $= EC_a = 110.93 \times 58.5 = 6489.5$ watts.

Total electrical energy in lamp circuit

$= eC = 108 \times 52.5 = 5670.0$ watts

Net eff. $= \frac{eC}{\text{H.P.} \times 746} = \frac{82}{100}$ or H.P. $= \frac{5670 \times 100}{82 \times 746} = 9.26.$

2. In a shunt generator, the resistance of the armature is .02 ohm; of the shunt field 20 ohms; of the lamps and mains .4 ohm; voltage at terminals 80. Find the total current, lost volts, percentage of loss in the armature and in the field magnets, and the current through the shunt field.

$$e = C_s r_s \quad \text{or } C_s = \frac{80}{20} = 4 \text{ amperes,}$$

$$e = CR \quad \text{or } C = \frac{80}{.4} = 200$$

$$C_a = C + C_s = 200 + 4 = 204 \text{ amperes.}$$

$$\text{Lost volts} = C_a r_a = 204 \times .02 = 4.08 \text{ volts,}$$

$$E = e + \text{lost volts} = 84.08 \text{ volts.}$$

$$\% \text{ loss in armature} = \frac{4.08}{84.08} = 4.8\%.$$

$$\text{Watts lost in field} = eC_s = 80 \times 4 = 320 \text{ watts.}$$

$$\text{Total watts} = EC_a = 84.08 \times 204.$$

$$\% \text{ loss in field} = \frac{320}{84.08 \times 204} = 1.8\%.$$

3. In a given generator, the loss in the armature is 1000 watts, in the field magnets 600 watts, hysteresis and other losses 280 watts, loss in engine 5920 watts. If 57,800 watts are supplied to the engine, how many 16 c. p. lamps at 4 watts per c. p. can be lighted? What is the commercial efficiency of the plant?

Ans. No. of lamps 781.
Commercial efficiency 86.5 per cent.

4. A shunt generator, total E. M. F. 100 volts, resistance of field 16 ohms, of armature .12 ohm, of external mains .2 ohm. How many lamps taking .8 ampere and having a hot resistance of 100 ohms will this generator maintain?

If 9½ H. P. is applied to armature shaft, what is the gross and net efficiency, and energy in watts lost in field and in armature?

$$x = \text{No. lamps} \qquad e = E - C_a r_a = C_s r_s = CR,$$

$$R = .2 + \frac{100}{x} \qquad CR = E - (C + C_s) r_a = E - \left(C + \frac{CR}{r_s}\right) r_a,$$

$$\text{or} \qquad CRr_s + Cr_a r_s + CRr_a = Er_s \qquad C = \frac{8}{10} x$$

$$Rr_s = \frac{16 \times (500 + x)}{5x} = \frac{8000 + 16x}{5x}$$

$$r_a r_s = .12 \times 16 = \frac{192}{100}$$

$$Rr_a = \frac{12}{100} \times \frac{500 + x}{5x} = \frac{6000 + 12x}{500x}.$$

$$\text{or} \qquad \frac{8}{10} x \left(\frac{8000 + 16x}{5x} + \frac{192}{100} + \frac{6000 + 12x}{500x}\right) = 100 \times 16$$

$$x = 75 +,$$

$$C = \frac{8}{10}x = 60 \qquad R = \frac{75 + 500}{375} = 1.532,$$

$$e = CR = 60 \times 1.532 = 91.92 = C_s r_s. \qquad \therefore\ C_s = 5.745$$

$$C_a = C + C = 65.745.$$

Total energy $= EC_a = 100 \times 65.745 = 6574.5$ watts $= 8.813$ H.P.

Useful energy $= eC = 91.92 \times 60 = 5515.2$ watts $= 7.342$ H.P.

$$\text{Gross eff.} = \frac{8.813}{9.5} = 92.77\% \qquad \text{Net eff.} = \frac{7.342}{9.5} = 77.81\%.$$

Energy lost in armature $= C_a^2 r_a = \overline{65.745}^2 \times .12 = 518.7$ watts,

Energy lost in field $= C_s^2 r_s = \overline{5.745}^2 \times 16 = 528.08$,

Energy in lamp circuit $= C^2 R = \overline{60}^2 \times 1.532 = 5515.20$

or total energy $\overline{6561.98}$ watts.

5. A long shunt compound wound generator, working with 3.6 ohms in the regulator, is furnishing a current in the external circuit of 117 amperes with a difference of potential at the terminals of 108 volts. The resistance of the shunt is 32.4 ohms, of the series field .015 ohm, and of the armature .045 ohm. Calculate the lost volts, current in armature, current in the field coils and the efficiencies, the power applied at the shaft being 20 H. P.

$$e = C_s r_s \quad \text{or} \quad C_s = \frac{108}{32.4 + 3.6} = 3 \text{ amperes},$$

$$C_a = C + C_s = 117 + 3 = 120 \text{ amperes},$$

$$\text{Lost volts} = C_a(r_a + r_m) = 120(.045 + .015) = 7.2 \text{ volts}.$$

Total watts developed $= EC_a = (108 + 7.2) \times 120 = 13824$

" " utilized $= eC = 108 \times 117 = 12636$

" " supplied $= 20 \times 746 = 14920$

$$\text{Gross eff.} = \frac{13824}{14920} = 92.65\%.^* \qquad \text{Elec. eff.} = \frac{12636}{13824} = 91.4\%.$$

$$\text{Net eff.} = \frac{12636}{14920} = 84.69\%.$$

6. A compound wound long shunt generator, resistance of armature .023 ohm, of series field .012 ohm and of shunt 20 ohms, maintains 300 110 volt 20 c. p. lamps, each lamp requiring 4 watts per c. p. Find the total E. M. F. of the machine. Allowing 15 per cent for friction and other losses, find the H. P. of the engine required to run the generator.

Watts in external circuit $= 300 \times 20 \times 4 = 24000$

$\frac{24000}{110} = 218.18$ amperes in external circuit.

$$C_s r_s = 110 \qquad C_s = \frac{110}{20} = 5.5,$$

$$C_a = C + C_s = 218.18 + 5.5 = 223.68,$$

$$E = e + C_a(r_a + r_m) = 110 + 223.68 \times (.023 + .012) = 117.8 \text{ volts}.$$

$$\text{H.P. required} = \frac{EC_a}{746 \times .85} = \frac{117.8 \times 223.68}{746 \times .85} = 41.55.$$

7. A compound wound generator, long shunt, maintains a difference of potential between the mains of the external circuit of 80 volts. 260 incandescent lamps of 16 c. p. each are placed in multiple arc between the mains, each lamp requiring 4 watts per c. p. The resistance of the armature is .02 ohm, series coils .005 ohm, and shunt current is 7 amperes. Find the gross, net, and electrical efficiencies when 26 H. P. is applied to the shaft of the generator.

Ans. Gross eff. = 94.61 %.
Elec. eff. = 90.65 %.
Net eff. = 85.77 %.

8. A long shunt compound wound generator maintains a difference of potential of 80 volts between the mains of the external circuit. 250 incandescent 16 c. p. are placed in parallel on the mains and each lamp consumes 4 watts per c. p. Resistance of armature = .0177 ohm, of series coil = .005 ohm. Shunt current = 7 amperes. Find the gross, net, and electrical efficiencies when 25 H. P. is applied to dynamo shaft.

Ans. Gross eff. = 94 %.
Elec. eff. = 91 %.
Net eff. = 86 %.

9. The machine in the preceding example develops a total E. M. F. of 83 volts; find the number of 16 c. p. lamps, resistance 100 ohms, placed in parallel that it will maintain, allowing 4 watts per c. p. Resistance of shunt = 5.8 ohms.

Ans. 148 lamps.

10. A current of 10 amperes is sent through a series of 10 arc lamps, each of 3.8 ohms resistance, by a generator whose armature is making 1000 revs. a minute. The arc lamps are then replaced by 8 incandescent lamps, each of 120 ohms resistance and arranged in 4 series of 2 each; the armature is then made to turn at 1044 revs. per minute. The resistance of the generator is 3 ohms. Assuming that the E. M. F. developed is proportional to the speed; find the strength of current in each lamp. *Ans.* 1.7 amperes.

11. A given shunt generator gives a total E. M. F. of 100 volts when run at a speed of 1000 revs. per minute. The shunt resistance is 50 ohms. What total E. M. F. will this generator induce if run at a speed of 1500 revs. per minute, if the shunt field is kept constant? What will have to be the resistance of the shunt to keep the field constant? Neglect the resistance of the armature. *Ans.* E. M. F. 150 volts.
Resist. 75 ohms.

12. The total E. M. F. of a shunt generator decreases from 125 volts to 100 volts when the speed is reduced from 1200 to 1000 revs. per minute. The armature flux at the higher speed is 10,000,000 lines. (1) What is the armature flux at the lower speed? (2) What would be the

E. M. F. of the generator at the lower speed if the armature flux were kept constant at 10,000,000 lines? *Ans.* 9,600,000 lines.
E. M. F. = 104.2 volts.

13. A shunt generator gives a full load current of 100 amperes at a terminal voltage of 125 volts, and an excitation of 20,000 ampere turns is required. To give the same voltage at zero load, 15,000 ampere turns are required. Find the number of turns required in a series field to give constant voltage. *Ans.* 50 turns.

14. A series generator has a combined armature and field resistance of .1 ohm. It gives a terminal voltage of 98 volts with a current of 20 amperes when driven at a speed of 1200 revs. per min. Find the terminal voltage when driven at a speed of 1500 revs. per minute it delivers a current of 30 amperes, if this current increases the field flux by 50%. *Ans.* 184.5 volts.

15. A short shunt compound wound generator delivers 50 amperes of current at 110 volts at the terminals. Calculate the commercial efficiency. Resistance of shunt field 55 ohms, of series field .02 ohm, of armature .14 ohm. All losses except copper losses equal 700 watts.
Ans. 80.3%.

CHAPTER XIII.

RUNNING GENERATORS IN PARALLEL.

It is sometimes necessary to couple two or more generators together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. To increase the current it is usual to connect generators in parallel exactly in the same manner that electric cells are connected in parallel; that is, by connecting the positive terminals together to a common conductor and by connecting the negative terminals together or to a common conductor.

Suppose a ship's plant was composed of three units of 800 amperes each. As long as the current to be carried is below the capacity of one machine, it is very evident that only one machine would need be in operation. It would be better to allow the load on one machine to increase to its full capacity before starting another machine than to divide the full capacity of one machine between two machines, whether connected in parallel or not. A machine that is running at its rated capacity has a greater efficiency than when running at a reduced load. If one machine can deliver all the current necessary, besides the gain in efficiency, it is clear that there can be no good reason for running two, which would simply mean extra wear on the moving parts, extra lubrication, and the extra attention necessary from the dynamo tender.

When the current necessary increases above the capacity of one machine, then it is obvious another machine must be connected in circuit. Suppose 1200 amperes were called for; this could be delivered by one machine at its full capacity of 800 amperes, and by a second machine running independently at 400 amperes. The case now becomes different, for two generators are necessary and whether running singly or in parallel, the wear and tear, oil consumption, and attention are practically the same. One would be running at its highest efficiency and the other at a considerably

reduced efficiency. If any extra load was called for, it could only be thrown on the light loaded machine and this would involve extra care on the part of the tender that is not necessary, that of picking out the right bus bars to throw the switches on. This is a very slight matter, but it involves at least a question of time. If the two generators are connected in parallel, the total load of 1200 amperes could be equally divided between them, so each would take 600 amperes and the combined efficiency would be greater than when one is running at its highest and the other at a reduced efficiency. If extra load was now called for, it is immaterial on which bus bars the switches are closed, for all being in parallel any increase will be equally divided between the two machines. When the load is equally divided, there is a general balancing all around of the electric energy; no one part is being strained while another part is subjected to little or no strain; the engines of the generating sets are doing an equal amount of work; there is the same amount of loss in the field regulators, and the same heating effect in all the parts of the generator. Any sudden call for current falls on both machines alike and the evils, if there are any, of sparking and consequent shifting of the brushes are on each machine reduced by half.

The two machines should be kept in parallel until their combined capacity is equal to the current called for, and if that still increases, a third machine should be connected in parallel with the other two. If 1800 amperes were required it could be furnished with two machines in parallel, each producing 800 amperes, and the third machine would then only have to supply 200 amperes, but if all three were connected, there would be 600 amperes on each, and there would be no danger of overloading any one machine, any current being added now being divided equally between the three.

Connecting Shunt Machines in Parallel.

There is no difficulty in running shunt generators in parallel, all that is necessary is to be sure to have the correct terminals connected together. The chief precaution to be observed is that when an additional generator is to be switched into circuit its field should be fully excited and the armature running at full speed before it

is connected to the mains; otherwise the current from the mains might prevent the building up of the field and the induction of current.

Suppose it is required to couple in parallel a shunt machine *B* carrying no load with another machine *A* carrying load, and that both are adjusted to the same terminal or switchboard voltage. The fields of both are fully energized and equal and the speeds relatively the same, so the *total* E. M. F. developed by the two armatures is the same. This total E. M. F. is equal to the terminal voltage plus the volts lost in overcoming the resistance of the armatures, in each case being equal to $C_a r_a$. When coupled in parallel so that *A's* load is one-half what it previously was, the armature current is halved and the lost volts in *A* are now only half as great as before. Consequently *A's* terminal voltage will rise by the amount of half the original lost volts.

The lost volts in *B* when running unloaded are equal to the field current times the armature resistance and are negligibly small. After coupling *B* now has half the original current and the lost volts increase to a value equal to the lost volts of *A*, and in consequence the terminal voltage of *B* will fall.

Under these conditions, *A* would have a higher terminal voltage than *B* by an amount equal to the original lost volts of *A*, and *A* would still have the whole load and though *B* was in parallel, it would still be unloaded. If this difference existed in two machines that were each carrying approximately the same load before putting in parallel, the double load thrown on the one would produce serious results in heating and sparking if the circuit breakers did not properly function to open the circuit.

The above discussion presupposes equal speeds, though if one was heavily loaded it would probably slow down and if the resulting difference of terminal voltages was not too great, the engine governors might act to adjust the speed to bring the voltages within limits that the machine would take their equal share of load.

Before throwing in a machine in parallel with another, in addition to seeing that the polarity is the same in each, the terminal voltage of the one to be coupled should be 2 to 3 volts higher than the one carrying the load.

Connecting Series Machines in Parallel.

Two series machines cannot be directly connected in parallel without some additional connections. If they were connected simply in parallel they might function if the E. M. F. at the terminals could be kept the same, and the internal resistances of each were exactly equal, but this could hardly occur. If the E. M. F. of one fell the slightest, current from the other would flow through the series coils in the opposite direction tending to weaken the current still more and reverse the polarity and in the end finally running it as a motor. To obviate this, not only the terminals of the machine are connected in parallel but the *brushes* are also connected by a conductor called the *equalizer*. If now either generator tends to slow in speed, current from the other will flow through the equalizer and through the series coils in the same direction as that of the generator itself, thereby building up the field and increasing the E. M. F. This equalizer also prevents any reversal of polarity, a very necessary precaution in parallel running.

Connecting Compound Generators in Parallel.

The only trouble in connecting compound generators in parallel arises from the series coils, the shunt being connected directly in parallel without any other connections, exactly as in the case of shunt generators. The series coils are connected with an equalizer exactly as in series generators, so for compound generators, it simply amounts to connecting the brushes of same polarity together as well as connecting the terminals.

Necessity of an Equalizer.

The equalizer helps to divide the load more exactly among the different machines. If there were no equalizer, as seen in series machines, the current from each armature would flow through its own series coil. When the load is increased, it might happen that one machine, being a little more sensitive than another, would take more than its share of the load, and this extra current going through its series coils would strengthen its field and cause it to generate more and more current, until it might blow its fuse and

open the circuit. Another reason is given under the connection for series machines, that is, the difference of E. M. F. whereby one would tend to run another as a motor.

Equalizing the Load.—By coupling all the machines to the equalizer so that there is a common connection between the armature and the series coils, the currents from all the armatures unite and then divide among the different series coils. If one armature tends to deliver more than its proportion of the whole current, it strengthens the current in the series coils of all the machines and

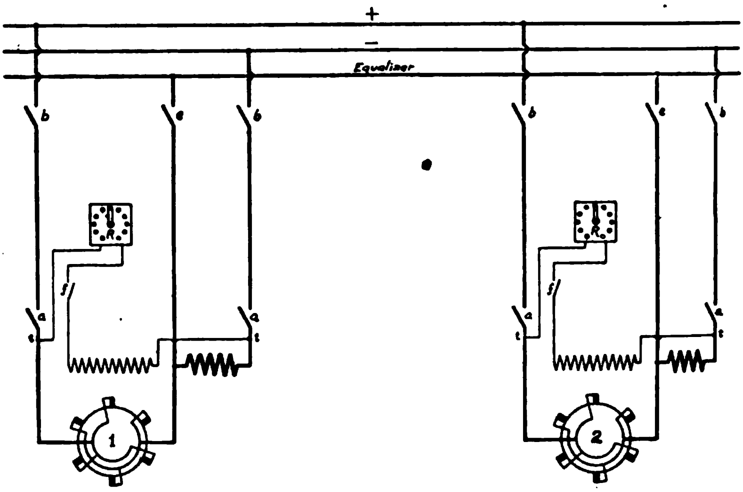


FIG. 87.—Parallel Connections.

not its own alone. If one tends not to take its full share, some of the current from the other machines goes through its series coils and helps build up its field so that it delivers more current.

Operating in Parallel.

Fig. 87 shows the connections of a modern generator to the bus bars on the switchboard. *R* shows the rheostat in series with the shunt field, a field switch *f* being introduced in circuit.

On the headboard there are two single-throw switches, one for each pole of the generator, represented by *a, a*. In addition, not

shown, there is a double pole circuit breaker and a switch for shunting the series coils or for short-circuiting the series coils. On the switchboard, there are independent bus switches shown at *b, b,* for connecting the generator leads to the bus bars. The common equalizer bus bar is shown under the current bus bars and to it is connected the equalizer from each generator through equalizer switches on the switchboard, shown at *e, e.*

Suppose No. 1 is running singly and delivering current to the bus bars, then all the switches *a, a, b, b,* and *f* would be closed. It is desired to connect No. 2 in parallel with it.

1. See all the switches on No. 2 open; these are, from the figure, the headboard, equalizer, bus bar switches, and field switch.

2. Close equalizer switch *e* on No. 1.

3. See that the resistance in field rheostat is turned to point marked "Low," all resistance out.

4. Close the shunt field switch *f*.

5. See that the voltmeter is connected on terminals for No. 2.

6. Start engine and bring it up to speed (shunt field being energized, E. M. F. will build up, and there being no resistance in rheostat will rise rapidly).

7. Move rheostat arm till E. M. F. rises considerably above the normal and then move it until it is about 2 volts above the normal.

8. Close equalizer switch *e* on No. 2.

9. Close bus bar switches on buses on which it is desired to run.

10. Close right-hand switch *a* on headboard. (This must be the one that has the series field.) This excites the series field through the equalizer from the other machine.

11. Close left-hand switch on headboard. (The one opposite to that which has the series field.)

12. Regulate load by field rheostat.

To cut out a machine that is running in parallel with another, the opposite method of procedure is followed.

1. Trip circuit breaker. (It is not necessary to open the headboard switches independently.)

2. Open bus bar switches.

3. Open equalizer switch.

4. Turn rheostat and when voltmeter stops moving toward zero, open field switch.

5. Stop the engine.

NOTE.—For operating in parallel with standard switchboard, see under standard switchboard, Chapter XXIII.)

In the switchboard that was the standard for many years (Fig. 266) to connect in parallel, it was only necessary to see that the machines were poled alike, that they had the same E. M. F., that the load was approximately divided by means of the circuit switches, and the equalizing switch closed. Closing this switch, which is a double switch, connected one set of mains in parallel and connected the equalizers from each generator, the other set of mains being permanently connected. The load was afterwards adjusted by the shunt field rheostats.

CHAPTER XIV.

THEORY OF MOTORS AND MOTOR CONTROL.

An electric motor may be defined as an electric machine by which electric energy in the form of electric currents is converted into mechanical energy by the operation of conductors carrying currents revolving in a magnetic field. Machines are divided into types of constant potential, constant current and alternating current as in the case of generators, but as the system of supply on board ship is of constant potential and continuous current, only such types that come under that head will be considered and their general principles explained, together with some of the uses to which they are applicable.

General Principles.

The elementary principle of the generator was explained by the action of a straight conductor moving across a magnetic field, and in which it was shown that the power used to move the conductor was converted into electrical energy, while at the same time it overcame a force which exerted a drag on the conductor. If the conductor is supplied with a current from an external source the same drag exists on the conductor and if not overcome will cause the conductor carrying the current to move across the magnetic field. This motion will itself generate an E. M. F. in the conductor, which by Lenz's law tends to stop the motion of the conductor.

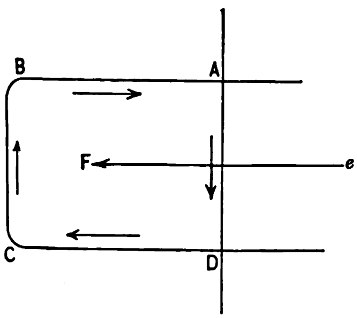


FIG. 88.—Illustrating the Principle of the Motor.

In Fig. 88, current is forced by some external means through

the straight wire AD fitted to slide along the portions AB and CD and to form portion of a closed circuit $ABCD$. The whole circuit is placed in a uniform magnetic field of intensity H, perpendicular to the plane of the paper.

A C. G. S. unit of current exists *when one centimetre of its conducting length is urged across a magnetic field of unit intensity with a force of one dyne.*

If the length of the conductor AD is l centimetres, and strength of current C absolute amperes, then the force urging the conductor across the magnetic field is

$$F = HlC \text{ dynes.}$$

The work done by this current moving the conductor at the rate of v centimetres per second is Fv ergs.

The motion of the conductor through the magnetic field induces in the conductor an E. M. F. (since E. M. F. is equal to the number of lines of force cut per second) equal to

$$E = Hlv \text{ absolute volts,}$$

and this E. M. F. opposes the flow of current in the conductor.

The work done by the current is Fv ergs, or

$$Fv = HlCv \text{ ergs;}$$

and since $E = Hlv$, the work done $= EC$ ergs per second, or

$$\text{work done} = EC \text{ watts.}$$

The work spent by the current goes to keep up the motion of the conductor.

Application to Practical Apparatus.—The general principle upon which all electric motors work is that **a conductor carrying a current will, when placed in a magnetic field, tend to move in such a direction as to embrace the greatest possible number of lines of force.**

Having seen the general principles under which generators work, we shall best understand the motor by considering it as a generator worked backwards; that is, a magnetic field is produced by an electric current, and currents are made to circulate in conductors wound on an armature, being supplied from some outside source.

The conductors carrying currents produce magnetic fields around them, and the resultant of these two fields tends to move the conductor, and if properly arranged mechanically, to produce rotation.

Figure 89 represents two conductors lying in the air spaces between two magnet pole pieces *N* and *S* and a cylindrical magnetic core. The air space is a magnetic field due to the poles *N* and *S*, the field due to these poles being represented by the straight lines running from right to left through them and the iron core, the positive direction being indicated by the arrow heads. The two conductors are marked, one *UP* representing a current flowing towards the observer as the figure is viewed, the other *DOWN*, flowing away from the observer.

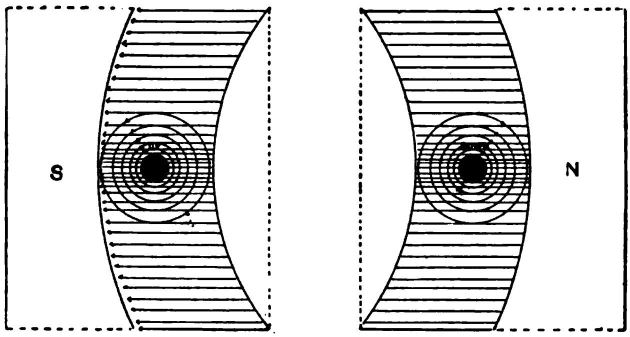


FIG. 89.—Separate Magnetic Fields.

The positive direction of the magnetic field due to the current marked *UP* is, according to the laws of induction, anti-clockwise viewed from this side and is shown as a series of concentric circles around the conductor. The field due to the current marked *DOWN* is similarly shown, the positive direction being clockwise. These two independent conductors may be considered to form part of a closed coil, the current running down on one side, through a connecting piece on the end of the core, parallel to the lines of force due to *NS* and up on the other, the two ends being connected with the source of supply of current.

If the magnetism of *N* and *S* is steady and the current through the coil is continuous and steady, the figure would represent the

effect, as far as the lines of force are considered, if there were no reaction between the fields. But there is reaction between them, the result being a compound magnetic field representing the resultant of the forces due to the poles and the forces due to the currents flowing in the conductors.

Fig. 90 shows the resultant field in the air spaces due to the magnetic field of the poles and the fields due to the current flowing in the conductor under the same conditions as stated above. The resultant field may be shown experimentally or the resultant directions of the lines of force may be proved mathematically. Remembering that the lines of force tend to shorten themselves, there being tension along them and pressure at right angles, it is clear

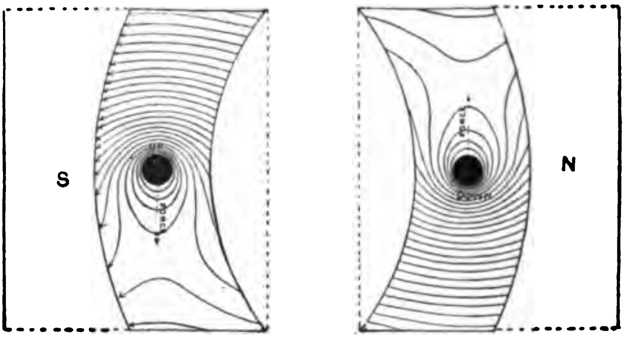


FIG. 90.—Resultant Magnetic Field.

that the pressure of the lines above the conductor marked *UP* will tend to force that conductor towards the bottom of the page as shown by the arrow, and similarly the conductor marked *DOWN* will be urged towards the top of the page.

If these conductors form part of a coil and are secured to the core which may be balanced on a shaft, the pull on one side and the push on the other side of each conductor will tend to cause revolution of the core. The tendency to revolve will be measured by the product of the force due to the current and the horizontal distance of the conductor from the center of the core. As the coil revolves, the horizontal distance between the conductor and center becomes smaller, approaching zero, which it is when the two conductors are

vertically over one another. The arm now being zero, the tendency to turn is zero, or the conductors will come to rest. In this position, the coil is now embracing the greatest number of lines due to the magnets, illustrating the principle already stated that a conductor carrying a current placed in a magnetic field will tend to move so as to embrace the greatest possible number of lines of force.

By arranging a series of coils around the core it is very evident that continuous rotation would be the result, for when one coil was in the position of zero tendency to turn, one at right angles would be in position of greatest tendency.

Torque.—It has been shown that the force developed by the current flowing in the conductor is dependent upon the intensity of the field, the current flowing, and the length of the conductor, or

$$F = HlC \text{ dynes.}$$

This force acts at right angles to the conductor and directly on it, and the total force developed is called the *drag* on the conductors. It is the force of this drag applied at the radius of the circle representing the cross-section of the core on which the conductors are wound that gives rise to the tendency to turn about a fixed axis. This tendency to turn is the twisting moment and is called the **torque.**

The torque is the product of two factors, force and distance, which produce work.

Distance or length divided by time gives velocity and work divided by time gives power.

$$\text{work} = \text{force} \times \text{distance}$$

$$\frac{\text{work}}{\text{time}} = \text{force} \times \frac{\text{distance}}{\text{time}},$$

or

$$\begin{aligned} \text{power} &= \text{force} \times \text{velocity} \\ &= \text{force} \times \text{radius} \times \frac{\text{velocity}}{\text{radius}} \\ &= \text{torque} \times \text{angular velocity.} \end{aligned}$$

The power absorbed by a motor is, as in the case of the power developed in a generator, the product of volts and amperes;

or

$$\text{volts} \times \text{amperes} = \text{torque} \times \text{angular velocity.} \qquad (1)$$

The angular velocity is expressed in *radians* per second, a radian being the angle whose arc equals the radius, so in one revolution there are 2π radians, and the expression for angular velocity is $2\pi n$.

Substituting in equation (1), we have

$$\text{watts} = \frac{2\pi nT}{10^7}$$

where T is the torque expressed in ergs, and 1 watt $= 10^7$ ergs per second.

If T is expressed in ft.-lbs., we have

$$\text{watts} = 2\pi nT \times 1.356.$$

Since
$$1 \text{ H. P.} = 746 \text{ watts}$$
$$= 550 \text{ ft.-lbs. per second,}$$

or
$$1 \text{ ft.-lb.} = 1.356 \text{ watts.}$$

Since
$$E = \frac{nZN}{10^8} \text{ volts}$$
$$T = \frac{ZNC}{1.356 \times 10^8 \times 2\pi}. \qquad (2)$$

Expression (2) shows the important fact that the *torque is independent of the speed,* and depends only on the current flowing through the armature and on the magnetism.

Referring again to equation (1), as the torque depends on the current, the speed must depend on the volts, giving the two important facts; first, that the **torque developed by a motor depends on the current absorbed** and, second, that its **speed for a given torque depends upon the E. M. F. at the terminals of the motor.**

Applied and Counter E. M. F's.

In Fig. 91 suppose there are two machines in all respects alike as to the winding of their armatures, and the fields of each are permanent, either due to permanent magnets or from current from some external source. The armature of the motor *M,* is directly connected to that of the generator *D,* and is supplied with current from it. If the armature of *M* is stationary, the only E. M. F. required to send a current through the conductors is that due to the resistance of the armature winding. If the torque due to this current is greater than the resistance to motion around the axis, the armature of *M* will turn, as explained.

The motion of the armature coils of *M* through the magnetic field induces an E. M. F. exactly similar to the case of the generator, and a consideration of the relative directions of the lines of force and of rotation will show that this E. M. F. is opposed to that of *D*. In each case, the windings of *D* and *M* are such that the induced current for the same direction of rotation tends to flow towards the upper brush, so the E. M. F. generated by *M* is opposite to that developed by *D*.

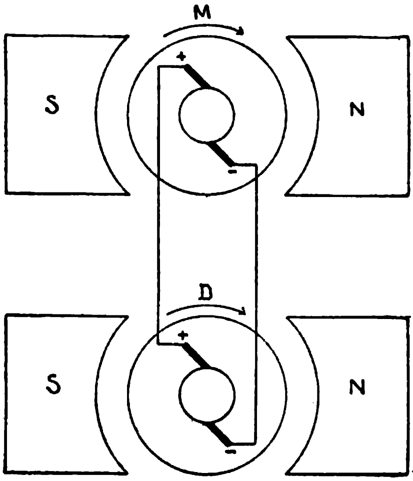


FIG. 91.—Illustrating Counter E. M. F.

The E. M. F. of the supplying generator is called the **applied E. M. F.** and the opposing E. M. F. the **counter E. M. F.** or **C. E. M. F.**

The counter E. M. F. cannot be measured directly, as a voltmeter connected to the motor terminals would show the same voltage as that of the generator terminals, less the drop in the leading wires.

In a generator, the torque is supplied by the mechanical power, being opposed to and overcoming a counter torque that is acting on the armature conductors; the overcoming of this counter torque being a measure of the power necessary to drive the armature.

Here in the motor we have the opposite effect, the E. M. F. supplied by the external source being opposed to and overcoming a counter E. M. F., and this counter E. M. F. being a measure of the power absorbed by the motor.

The counter E. M. F. being opposed to the applied E. M. F. diminishes its effect, so that the current through the armature is lessened and consequently the torque is less as the speed is increased. If the torque is still greater than the opposition to motion, the speed of the armature will increase, the current and torque decrease, until the torque exerted by the current is just equaled by the resistance to motion, of whatever nature that may be, when the speed will remain constant. So we see at the outset the important principle that **the greater the speed the less the torque to produce the same amount of power.**

When the speed becomes constant, the difference between the applied and the counter E. M. F's. represents the drop through the armature, or the difference of potential required to force the current through the armature resistance. The product of this difference of potential and armature current represents the energy lost in heating the armature coils. This becomes greater as this difference increases and is a maximum when the armature is at rest, when there is no counter E. M. F., so it is seen that at this time, if the armature does not turn, all energy is lost, and a very large current would flow, so large in fact as to endanger the armature. On this account it is usual to insert in series with the armature current a resistance called a starting resistance which is made large enough to allow a small current to flow at first, producing an initial torque, and as the speed increases and counter E. M. F. increases so as to reduce the current, the starting resistance is gradually lessened, until at full speed when very little current is flowing through the armature, all the resistance is out.

Of the total E. M. F. applied to the motor, part is expended in overcoming the resistance of the armature, and is energy lost, while the difference, or the counter E. M. F. represents the energy required to keep the armature in motion, and represents the energy expended in overcoming friction losses and core losses, exactly as in the case of the generator, and in overcoming the resistance to

motion of whatever nature that may be; this latter being the mechanical work done by the motor.

To a certain extent the motor is entirely automatic as regards relation of current to external load. A certain amount of current is necessary at all speeds to furnish the torque necessary to overcome the motor losses, and if there is not sufficient current to overcome these losses, there will be no motion. Suppose the motor is running at a certain speed with a certain load, or doing a certain amount of external work, then if the load is increased, the current flowing at that time cannot furnish sufficient torque to perform this extra work, so the motor slows down. This slowing down reduces the counter E. M. F. and consequently the current increases, and the torque is now sufficient to perform the extra work the motor is called on to do. If the load is decreased, the armature has too much torque, so it speeds up, thereby increasing the counter E. M. F. and decreasing the current, and thereby the torque to the proper amount.

All that has been said regarding motors so far has reference to a field of practically constant value, in the theoretical case, the field being supplied by some constant potential source. In practical applications the field magnets of constant potential motors may be either shunt wound or series wound, or a combination of these two, corresponding to the compound-wound generator, called differential wound.

Fundamental Equation of the Motor.

The E. M. F. induced by a motor armature revolving in a magnetic field is calculated in exactly the same manner as that for a generator, and in general terms is

$$E = nZN, \tag{3}$$

where the symbols have the same signification as previously given.

Equation (3) represents the motor E. M. F. or counter E. M. F. The difference between the applied E. M. F. and the counter E. M. F. represents the drop in voltage that takes place in the armature resistance and is equal to $C_a r_a$, and, therefore,

$$\mathfrak{E} - E = C_a r_a ,$$

or

$$\mathfrak{E} = nZN + C_a r_a . \tag{4}$$

Referring to the fundamental equation of the generator, the Z used in equation (4) is $\frac{pZ}{p'}$ where p and p' have the same signification as there given.

From equation (4)

$$n = \frac{\mathfrak{E} - C_a r_a}{ZN} \tag{5}$$

and

$$C_a = \frac{\mathfrak{E} - nZN}{r_a}. \tag{6}$$

Equation (6) shows that C_a cannot be calculated from Ohm's law in a running motor, and only holds when $n = 0$,

when $$C_a = \frac{\mathfrak{E}}{r_a}.$$

Under this condition, owing to the small value of r_a, C_a would be excessive, necessitating the insertion of the starting resistance in series with the armature.

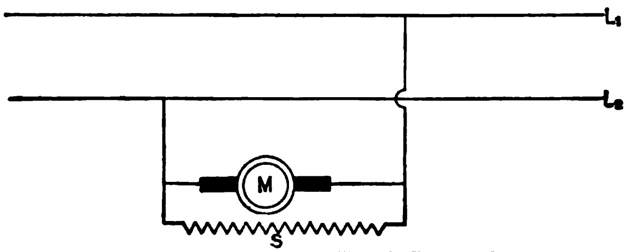


FIG. 92.—Elementary Shunt Connections.

Shunt Motors.

The elementary connections of a shunt-wound motor are shown in Fig. 92, though it must be understood that this is given for a machine that is running; the starting requiring a separate device.

In the figure, L_1 and L_2 represent the supply mains, M the motor armature, and S the shunt field.

In shunt-wound motors from a constant potential source of supply, the difference of potential at the field terminals being constant, the magnetizing force is constant and all that has been said

in reference to motors in general will apply to this case. The field being constant, the counter E. M. F. will depend on the speed, and, as has been shown, the amount of current taken varies automatically with the external load, and variations in load will make but slight changes in speed. There is no danger of a shunt-wound motor attaining such a speed as to become dangerous, for as it tends to speed up, the current and consequently the torque is decreased, and it will only attain a speed such that the torque just balances the friction or whatever the resistances to motion may be.

On account of the small variations in speed, shunt motors are used where nearly a constant speed is necessary or on moving parts that would be damaged if the speed became excessive, such as on portable fans, or ventilating sets, or pumps, and on machinery where there is not much starting and stopping, or where excessive torque is not required at starting. One disadvantage of the shunt motor is that, the field being always constant, there is always a constant loss of energy.

The previous explanation may be seen from an examination of the formulæ deduced.

When a shunt motor is running light or unloaded, the torque required to drive it is only that necessary to overcome the friction of the bearings and air friction, and is consequently small, and from equation (2) C_a must be very small. Consequently the drop through the armature $C_a r_a$ must be very small and can be neglected, since both C_a and r_a are very small, and from equation (5)

$$n = \frac{\mathfrak{E}}{ZN} \text{ at zero load.} \tag{7}$$

As nZN is equal to E, the applied E. M. F., it is seen that at zero load, a shunt motor runs at such a speed as to make its counter E. M. F. sensibly equal to the applied E. M. F.

When load is thrown on a shunt motor, the tendency is to slow somewhat and thereby decrease nZN, the counter E. M. F. According to equation (6) C_a will then increase, as will also the torque T according to equation (2), and it is the increase of the torque which enables the motor to carry the increased load. The decrease of counter E. M. F. must be sufficient to allow enough current to flow to develop the necessary torque. If N is constant,

nZN could only vary by a drop in n, but due to demagnetizing action of the armature current, N varies, so the change in nZN is produced both by N and n, so the actual change in the speed is less than if the field was absolutely constant.

Relation Between Field and Speed.—If the field is decreased, nZN, the counter E. M. F. is decreased, and a sudden increase of armature current results, as shown by equation (6). The increased current produces more torque than is necessary to carry the load, so the motor speeds up until the increase of nZN reduces the current to the value to give the required torque.

Relation Between Brush Lead and Speed.—A generator has its maximum E. M. F. when the brushes are at zero lead, or have no lead. In the case of a shunt motor, the speed is a minimum when the brushes have zero lead, and any movement of the brushes either forwards or backwards, will increase the speed and this is particularly noticeable in a motor running light.

When the brushes are moved from the zero position, the counter E. M. F. is reduced, the speed remaining unchanged. As a result a greater current flows, producing an increased torque which causes the motor to speed up until the counter E. M. F. attains a value so as to reduce the current to the value necessary to supply the required torque.

Speed Control.—It has been shown that the speed of a shunt motor varies very little with changes of load from zero to full load, and when used for power where a varying speed is required, special arrangements are necessary.

Armature Resistance Method.—When the load on the motor is constant, its speed may be controlled by inserting resistance in series with the armature. When the resistance of the armature is large or when a large resistance is in series with the armature, equation (6) shows, that for a loaded motor, the large C_a necessary to produce the required torque can only be obtained by a large value of the numerator, $\mathfrak{E} - nZN$, and this can only be obtained by a large change in n in order that nZN can be considerably less than $\mathfrak{E}$.

On zero or light load, C_a is small, so the speed is not much affected by having r_a, or $r_a +$ the resistance, large. This consideration shows that the change in speed for loads over a wide

range cannot be satisfactorily effected by changes in armature resistance, but for loaded motors it is effective.

Field Resistance Method.—Equation (7) shows the zero load, and consequently full load to practically the same extent, may be changed by varying N. This is effected by means of a resistance in series with the shunt winding, which can be increased or decreased, thus decreasing or increasing the field current and N proportionately.

The regulation by this means is limited, for the field cannot be increased above its saturation point, nor can it be decreased below a certain value, for the torque decreases with the field, and the magnetic reactions in the armature may overpower the weakened field.

Other methods of control applicable to motors in general will be discussed later under the head of Motor Control.

Series Motors.

With this form of motor the field varies with the strength of current. If the load on a series motor is reduced, the increase of torque, or rather the excess, causes the speed to increase, thereby diminishing the current and weakening the field, again causing the speed to increase to a greater extent to increase the counter E. M. F., than in the case of the shunt motor. If the load is increased there is a deficit of torque, the speed falls, the current increases, thereby increasing the field so that the speed must decrease considerably in order to reduce the counter E. M. F. to the proper amount. The speed, therefore, of the series motor varies considerably with the changes in load, and on this account is used on hoists, such as ash hoists, boat hoists, ammunition hoists, or where there are wanted both variations in the load and speed.

The field of the series motor may be varied in exactly the same way as the E. M. F. in a series generator is varied by cutting out some of the series turns, or introducing a resistance in parallel with the series windings.

One disadvantage of the series motor is that if by any chance all the load is thrown off, the required current is very small, and so weakens the field that it requires a very high speed to generate

the proper counter E. M. F. and the speed may become so great as to rack the armature to pieces. An advantage of this motor is that it allows a strong current and consequently strong torque at starting, a very important element in getting heavy weights such as anchors, or boats, or turrets started.

Regulation.—In certain cases, a good method of regulating these motors is to regulate the E. M. F. of the supplying generator, starting with a high E. M. F. where great torque is required, and cutting it down as the speed rises. This is not as wasteful as introducing a resistance in the main circuit, and keeping the supplying E. M. F. constant as is sometimes done.

Compound Motors.

As the object of compound generators is to produce a constant potential at all external loads, so the object of compound or differentially wound motors is to produce constant speed under all external loads. This problem is solved by building motors with a compound field consisting of the ordinary windings of the shunt motor with a few turns of series windings, so arranged that they are opposed to each other, one tending to magnetize and the other to demagnetize. The effect of this method of winding can be illustrated by taking the case of a shunt motor with a constant potential, running at a constant speed. If the load is suddenly reduced, the excess of torque causes the motor to increase in speed which will increase the counter E. M. F. and cut down the armature current. This would tend to reduce the torque, but on account of the internal resistance of the armature, all of the current is not available for this purpose so the speed will not fall to exactly what it was before. Now in the case of the compound motor, at all times there is a constant demagnetizing effect due to the series windings, and as the current is decreased, as the armature speeds up, this demagnetizing effect is lessened, or the field strengthened, so the required counter E. M. F. is obtained without any increase of speed; or, in other words, it remains constant. It is evident then there should only be enough series turns to make up for the energy lost in overcoming the motor resistances, friction and core losses.

The speed at which the compound motor runs should be the

same speed as that, if used as a generator, it would yield an E. M. F. equal to that of the supplying source. At this speed it should run so fast as to reduce the armature current to a minimum. By making the shunt field strong enough the required speed can be made as low as desired.

If the speed is to be constant, the counter E. M. F. must be constant, and as the load changes, the torque and consequently the armature current changes, so the counter E. M. F. can only be kept constant by changes in the magnetic field which is accomplished by the series turns, the field diminishing as the current increases and vice versa.

It is usual in starting differently wound motors to have an arrangement for keeping the series turns out of circuit until the motor has speeded up, for if the series and shunt windings are properly proportioned to govern exactly, there might not be any resulting magnetism, or if one overbalanced the other, the motor might start to run the wrong way.

Other Method of Compounding.—One other method of compounding has been to wind two separate circuits on the armature, one to receive the supplied current, and the other acting as a generator, inducing its own current and which is connected to the series windings. As the armature speeds up, the induced current becomes greater and tends to increase the field, so the counter E. M. F. is obtained by a lower speed. If the armature slows down, the induced current is lessened, the field magnetism is lowered, and a higher speed is necessary to produce the counter E. M. F.

Generators as Motors.

Generators designed for continuous currents may be used, in all cases, as motors with some slight changes. A **series generator** used as a motor will run in the *opposite* direction to that in which it must be driven in order to build up as a generator.

Fig. 93 shows a diagrammatical sketch of a series generator and series motor.

In Fig. 93 the left-hand figure represents a series generator, the curved arrow representing the direction of rotation of the armature, with the resulting current in the external circuit and

through the armature represented by the arrows in those parts. The arrow A represents the resultant mechanical force between the field and armature current and in the generator the counter force that the power driving the armature overcomes.

With given connections of field to the armature, the *relative* direction of current through field and armature is the same whether used as a generator or motor, and consequently there is *no* change in the mechanical force with which the field acts on the armature conductors. In the generator the power overcomes this force, but in the motor, it produces the motion, so consequently the force that has been overcome in the generator acts to produce *opposite* rotation when used as a motor.

It is immaterial which way the current flows when used as a motor, for the reversal of the supply current simply reverses both

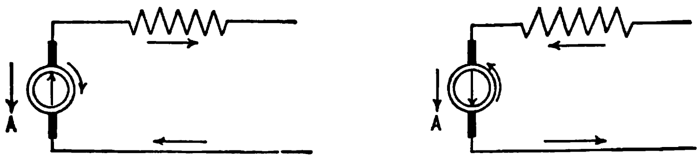


FIG. 93.—Series Generator and Motor.

the direction in the armature and in the field and does not change the relative directions, so there is no change in the force exerted by the field on the conductors.

To reverse the direction of the series motor, the armature current must be reversed without shifting the direction of the field current, by shifting the connections to the brushes.

A **shunt generator** with given connections of field to armature will run as a motor in the same direction that it must be run to build up as a generator.

Fig. 94 shows a diagrammatical sketch of a shunt generator and shunt motor.

In Fig. 94 the left-hand figure represents a shunt generator, the curved arrow representing the direction of rotation of the armature, with the resulting current in the various parts represented by straight arrows. The arrow *A* represents the resultant

mechanical force between the field and armature current and in the generator, the counter force that the power driving the armature overcomes.

In the generator, it is noticed that the current in the armature and in the field are opposed to one another, while in the motor, they are in the same direction. Consequently, in the motor, there is a *relative* change in the direction of the armature and field currents and also there is a change in the mechanical force that represents the resultant action of the field on the armature conductors. In the generator this force is overcome by the power driving the armature, and the force being reversed, now drives the armature of the motor in the *same* direction.

In this case, also, it is immaterial which way the current flows in the motor circuit for a given connection to the brushes; for the

FIG. 94.—Shunt Generator and Motor.

reversal of the supply current simply reverses the current in both armature and field without producing any relative change, so there is the same change in the mechanical force, which being opposite to that of the generator, causes the motor to revolve in the same direction.

To reverse the direction of rotation of the shunt motor, either the current through the armature or through the field should be reversed, *but not both.*

Compound Generator.—A *compound-wound* generator when run as a motor will run in either direction, depending on the relative strength of the two fields.

Efficiencies of Motors.

As in the case of generators, there are three efficiencies representing the relation between the energy furnished the motor, the energy

absorbed by the motor, and the energy supplied by the motor. Of these, the first two are electrical quantities and the third mechanical, all of which must be expressed in the same units either electrical or mechanical to obtain a proper percentage of efficiency.

Gross Efficiency.—This is a term given to express the relation between the power actually absorbed by the motor and the total power supplied to the motor at the terminals. As in the notation previously used, if $\mathfrak{E}$ is the difference of potential at the motor terminals, and C, the current flowing in the supplying mains, then the total energy in watts supplied to the motor is $\mathfrak{E}C$. If E represents the counter E. M. F. and C_a the armature current, then the total power in watts absorbed by the motor is EC_a, and the gross efficiency would be $EC_a \div \mathfrak{E}C$. In the series motor $C_a = C$, and in the shunt motor $C_a = C - C_s$, the latter term representing the shunt current.

Both $\mathfrak{E}$ and C can be directly measured by connecting a voltmeter at the terminals and connecting an ammeter in series with the supply mains. The difference between $\mathfrak{E}$ and E represents the volts lost in the armature, and as in the case of a shunt generator is equal to $C_a r_a$, or $\mathfrak{E} - E = c_a r_a$. C_s is calculated by knowing the difference of potential at the shunt terminals and the resistance of the shunt, for $\mathfrak{E} = C_s r_s$. Thus knowing C and C_s, C_a is known, or it might be measured directly by connecting an ammeter in the armature circuit. Knowing C_a, the lost volts are known, which subtracted from $\mathfrak{E}$ will give E. The greater E is the greater the gross efficiency.

In the case of motors, the gross efficiency is really the efficiency of the motor *per se*, being entirely a relation of electrical quantities and corresponds to the electrical efficiency of a generator. This efficiency can be as high as it is possible to make E by reducing all core and friction losses and by making the internal resistance as small as possible.

Law of Maximum Activity.—There is a law of maximum activity which was confounded with the law of maximum efficiency in the early days when the working of motors was not as well understood as at present. The power utilized in a motor is the difference

between the total power supplied and the power lost in overcoming the internal resistances, or the heat loss, the C^2R loss.

If w is the power utilized,

$$w = \mathfrak{E}C - C^2R.$$

When w is a maximum, C has a value equal to one-half the value it would have if the motor was at rest, for

$$dw = \mathfrak{E} - 2CR,$$

which is a maximum when $dw = 0$, or

$$\mathfrak{E} = 2CR \text{ and } C = \tfrac{1}{2}\frac{\mathfrak{E}}{R}.$$

$\frac{\mathfrak{E}}{R}$ equals the current when motor is at rest, so *the maximum work is done when the motor runs at such a speed that the armature current is reduced to one-half what it would be if the motor is at rest.* This means that when the motor is doing work at its greatest activity its efficiency is only 50 per cent for

$$C = \frac{\mathfrak{E} - E}{R} = \tfrac{1}{2}\frac{\mathfrak{E}}{R},$$

or

$$2E = \mathfrak{E},$$

or, as before, the efficiency is $\frac{E}{\mathfrak{E}} = \frac{1}{2} = 50$ per cent.

Electrical Efficiency.—This is a term that represents the relation between the total power absorbed by the motor and the total power given out by the motor, the first being an electrical quantity and the second mechanical. The first term is the product of E and Ca, and it has been explained how they are obtained. The mechanical power developed at the pulley of the armature motor is the product of the torque developed and the radius through which it acts, in precisely the same way that the power exerted by the current in the armature is the product of its torque and the radius of the armature. If the torque is expressed in pounds force and the radius in feet, the work is expressed in ft.-lbs. which may be reduced to horse-power.

The torque can be measured in several ways; by finding the difference in tension of the sides of a belt that runs on the arma-

ture pulley, or by means of the Prony brake, which is simply an arrangement for measuring the friction exerted between the pulley and an arm connected to a scale which will measure the friction absorbed at any given speed. Still another method is by means of the Brackett cradle, in which the motor is mounted in a cradle and accurately balanced. When running with any load, the tendency of the field frame to turn around the armature axis by which it is balanced is measured as so many ft.-lbs., by finding how many pounds weight at a certain distance will balance this tendency, or the motor measures its own output.

Net Efficiency.—This is a term that expresses the relation between the total mechanical power produced by the motor and the total electrical power supplied, both of course being expressed in the same units. It has been explained how both of these factors are found and the net efficiency is simply the quotient obtained by dividing one by the other, and it is also numerically equal to the product of the other two efficiencies. The power supplied is called the *input* and that obtained the *output,* and the differences between these quantities represent the losses in the motor.

Motor Losses.

As stated above the total loss in a motor is represented by the difference between the input and the output and this loss is made up of the same elements as in the case of generators, part being electrical and part being mechanical losses, and made up of mechanical friction in the bearings, friction between the brushes and commutator, air friction of the revolving armature, core losses due to eddy currents and hysteresis, frame losses, due to eddy currents in the pole pieces and the copper losses in the field windings and armature conductors.

The difference between the total power supplied and the total power absorbed is represented by the heat losses in the field and armature, or is the power that is lost in overcoming the resistances of those parts. In a shunt motor, the field loss would be $C^2{}_s r_s$ watts and in the armature $C^2{}_a r_a$ watts. The total core and friction losses taken together is equal to the sum of all the losses minus the sum of the field and armature losses, and is also equal to the differ-

ence between the total power absorbed by the motor and the power developed by it.

Since the speed of a shunt motor is practically constant at all loads, the losses are practically constant at all loads, and they can be very approximately calculated by finding what current will run the motor free at its given speed. There is no output and the input represents the mechanical and core losses and the loss in the field, as the armature loss will be so small that it may be neglected.

As an example, suppose a shunt motor requires a current of 8 amperes at 80 volts when running free at 1500 revolutions. Armature resistance .04 ohm and shunt resistance 20 ohms.

Field current or $C_s = \frac{80}{20} = 4$, and $C_a = C - C_s = 8 - 4 = 4$.

Loss in field $C^2_s r_s = 4 \times 4 \times 20 = 320$ watts.
Loss in armature $C^2_a r_a = 4 \times 4 \times .04 = .64$ watts neglected.
Total input $\mathfrak{E}C = 80 \times 8 = 640$ watts.
Mechanical and core losses $= 640 - 320 = 320$ watts.

Now suppose the net efficiency was wanted when the motor was working with a current of 36 amperes.

As before $C_s = \frac{80}{20} = 4$ and $C_a = 36 - 4 = 32$.

Loss in field $C^2_s r_s = 4 \times 4 \times 20 = 320$ watts.
Loss in armature $= 32 \times 32 \times .04 = 41$ "
Mechanical and core losses (as above) $= 320$ "
Total losses $= 681$ "
This leaves $(80 \times 36) - 681 = 2199$ " as the output,
or the efficiency $= \frac{2199}{2880} = 76.4$ per cent.

As a matter of experiment this motor when absorbing 36 amperes and 80 volts, showed 2.97 H. P. at the pulley, or $2.97 \times 746 = 2214$ watts, which would give an efficiency $= \frac{2214}{2880} = 76.8$ per cent, showing that the mechanical and core losses calculated when running free must have remained constant under the increased load which was great enough to require 36 amperes.

In order to separate the total friction and core losses, that is, separate the loss due to mechanical friction, that due to eddy cur-

rents, and that due to hysteresis, it becomes necessary to make other connections and make observations at different speeds, as we saw under generators that eddy currents vary with the square of the speed, and hysteresis directly as the speed. An ordinary way of doing this is to separately excite the field magnets and to note the number of volts and amperes absorbed when the motor is running at different speeds with no load. Using the amperes as ordinates and the volts as abscissæ, curves can be plotted, the ordinates of which, being proportional to the current, will represent the losses at that current. If the curve is a straight line parallel to the axis of volts, all the losses are directly proportional to the current or there is no loss due to eddy currents, but if the curve makes an angle with the axis of volts, the increase of ordinates over those due to friction and hysteresis represent losses due to the eddy currents.

To further separate the friction losses from hysteresis loss the armature should be coupled direct to another similar machine running without a field excitation, when the increase of current necessary to run this second machine will be a measure of the frictional loss, which deduced from the other total loss independent of the eddy loss, will give the hysteresis loss.

Motor Control.

By this term is meant the operation of devices introduced between the supply lines and a motor by which the motor is stopped or started, and by which the direction and speed of the armature is controlled. The systems of control used in motors on ships of the navy are those generally known as the Automatic Rheostatic system, the Leonard system, the Day system, and the Panel system. The devices by which these systems are put in operation are generally known as Starting Panels or Controllers, which contain the necessary switches, fuses, resistances, etc., for controlling the current.

Operation of Motors.

If the armature of a motor at rest was suddenly connected to a source of supply of current, an abnormally large current would flow

through the armature owing to its low resistance. This arises from the fact that as the armature is at rest, it cannot develop any counter E. M. F. to reduce the incoming current. It does, however, do so the moment it commences to revolve and as its speed increases, counter E. M. F. is generated to sufficiently reduce the current to its normal flow.

To prevent this first sudden inrush of current, it is usual in all forms of motors that are to be used as motors alone to introduce a resistance in series with the armature, so that when the circuit is first established only sufficient current flows through the armature to produce sufficient torque to cause revolution of the armature.

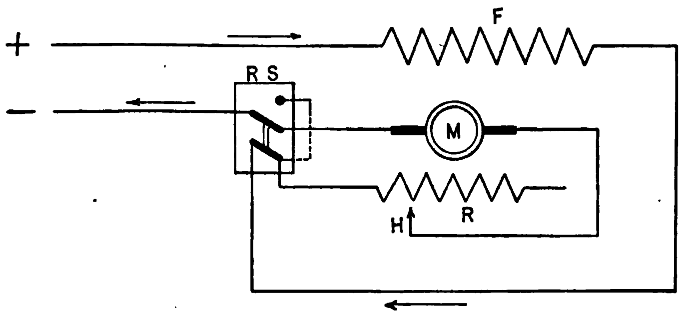


FIG. 95.—Control of Series Motor.

As soon as the armature starts to revolve and counter E. M. F. is generated, this reduces the supply current, so some of the resistance may be cut out which will allow more current to flow and greater torque to be produced. As the armature speeds up, the resistance is gradually cut out until the armature terminals are directly connected to the full voltage of the supplying mains and the armature is running at its full speed.

It has been previously shown that in order to reverse the direction of revolution of the armature that either the field current or the armature current must be reversed, *but not both.* In some cases of reversal the armature current is reversed and this might be considered the ordinary way, but in others to be mentioned later, the field current is reversed.

Rheostatic Control.

Series Motors.—This form of control is illustrated in the elementary diagram shown in Fig. 95.

To Start.—The field coil *F* is in series with the armature through the rheostat *R* and connected to the supply lines marked + and — through the reversing switch *RS*. When the switch *RS* is first closed, all the resistance *R* is in circuit, but as the armature *M* commences to turn and develop counter E. M. F. the resistance is gradually cut out until the arm *H* rests on the last contact of the resistance when the armature receives the full line voltage. This constitutes the rheostatic control for starting. In actual starting

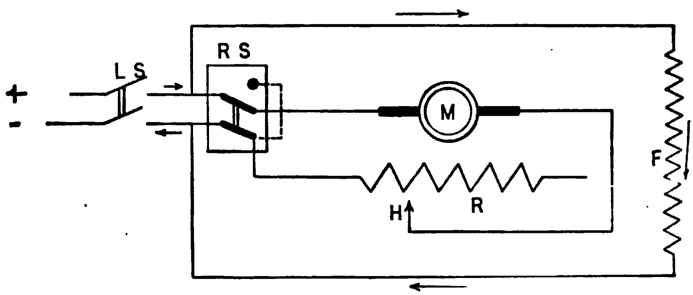


FIG. 96.—Control of Shunt Motor.

devices for series motors, the armature current and field current are connected to the mains at the same time by means of the switch or controller, after which the resistance in the field is gradually cut out.

To Stop.—To stop it is only necessary to reverse the operation of starting, moving the rheostat arm over the contact points until the last is reached when the field and armature current is broken at the same time by the switch. It is well to make the motions quickly to avoid the sparking that might occur when the circuits are broken.

To Reverse.—To reverse the direction of rotation of the armature it is only necessary to move the switch *S* to the other contact points shown, when an inspection will show that though the current through the field is in the same direction as before the direction

through the armature has been reversed. To do this, however, the armature should first be brought to rest and with all the resistance in circuit.

Shunt Motors.—The control for shunt motors is illustrated in the elementary diagram shown in Fig. 96.

In addition to the reversing switch, which in the case of series motor also acts as a starting switch, a shunt motor should be provided with a double-pole switch in the main line and the usual starting resistance.

To Start.—Close the double-pole switch *LS* which sends current through the shunt coils *F* and excites them at the constant potential of the line marked + and —, and it is important to note that in all cases the motor field is energized before any voltage is applied to the armature. The switch *RS* should then be closed one way or the other, sending current through the resistance *R* in series with the motor armature *M*. The resistance *R* is then gradually cut out as in the case of the series motor and the armature brought to speed.

To Stop.—The line switch *LS* should be opened, first cutting off the armature current, and as soon as the armature is at rest, the arm *H* should be run quickly back throwing in all resistance ready for starting again.

If the rheostat arm is moved first there is likely to be bad sparking or flashing when the off position is reached and when the line switch is opened there is apt to be a long arc endangering the field coil insulation.

Cause of Flashing.—This is caused by the self-induced current in the field as the field current commences to weaken. The induced current tends to keep up the field current and on account of the number of turns in the field winding and the iron core, the momentary current has a high E. M. F. which manifests itself when the circuit is broken by the spark, a manifestation of the tendency of the induced current to keep on flowing.

To Reverse.—When the motor is at rest, it is only necessary to shift the reversing switch *RS* to its other contacts, and it will be then seen that, as the field connections are beyond this switch, the

current through it will be as before, while the current through the armature is reversed.

Compound or Differential Motors.—These are started and stopped in exactly the same way shunt motors are, it being usually arranged that the compound windings (series) are not thrown in circuit until all the starting resistance is cut out and the motor is running at its full normal speed.

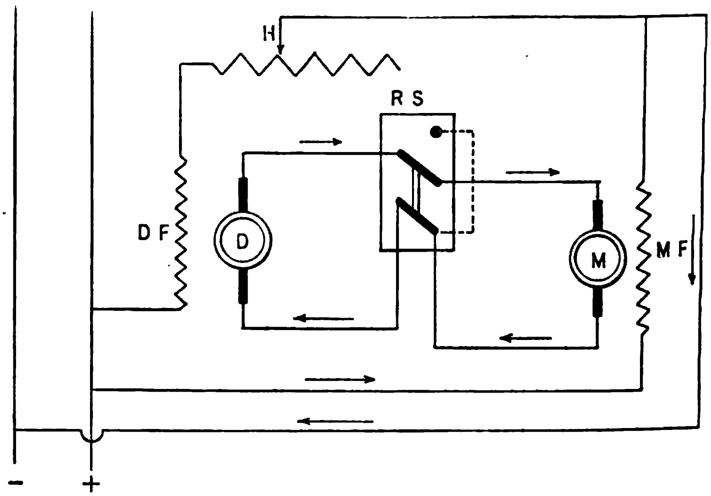


FIG. 97.—Ward Leonard System of Control.

The Leonard Control.

In the rheostatic method of control it is seen that in starting motors only a small portion of the line voltage is applied to the armature terminals at first, being gradually increased as the motor gets up its speed. It has also been shown that this is effected by means of a resistance in series with the armature, which with the armature resistance is sufficient to reduce the first current to about 1½ times the full-load current. Thus, about half the voltage applied is used up in this resistance, being equal to the current flowing times the resistance, and is dissipated as heat. This is a great loss in economy and the object of the Leonard control is to generate only

enough voltage to produce the desired current without the intervention of the wasteful resistance.

This system of control finds its greatest application to ship's motors in turret-turning and gun-elevating motors, and will be fully described later; at this time only the elementary principles being explained.

The elementary diagram illustrating this method of control is shown in Fig. 97.

In figure, *D* is a generator armature directly connected to the motor armature *M* through the reversing switch *RS, DF* is the generator field, and *MF* the motor field. The supply mains + and — are energized to full potential by some other source of power.

As long as the generator field is broken by the arm *H* being off the rheostat *R*, the field of the generator is not energized and there is no voltage generated in it, though the motor field is fully excited from the mains.

When *H* first makes contact with *R* a small current then flows through the generator field and the generator armature revolving in this field generates a small difference of potential which is impressed on the motor terminals. As soon as this voltage is sufficient to generate enough current to produce the necessary torque the motor armature commences to turn, and will attain a speed proportional to the volts impressed on its terminals and which in turn is the full amount generated by the generator.

By cutting out the resistance in *R*, the voltage of *D* gradually increases, the voltage at *M* increases the same, and the motor armature gradually speeds up.

By this method of control there is no wasteful energy in motor armature resistances and the changes of speed are gradual and can be absolutely controlled by the generator field rheostat from start up to the maximum speed.

The direction of rotation of the motor armature can be changed by shifting the reversing switch *RS*.

To slow the speed it is only necessary to cut in resistance in *R* and if this is done quickly the voltage at the terminals of *D* may fall much below that of *M* for the instant, in which case *M* will

now tend to act as a generator and will generate large currents, quickly slowing it down until the voltage reaches that of *D*.

If from any cause the voltage of *D* is cut off, and the load on *M* tends to rotate it, the motor will then act as a generator short-circuited at its terminals and the large currents generated will act as a counter drag on its conductors and quickly bring it to rest.

The Day Control.

This system of control finds its greatest application in hoisting work, in which it is necessary to have the hoisting mechanism overhaul itself as quickly as possible as well as to have its speed absolutely controlled. When a weight is to be lowered, it may not exert sufficient force to overcome the friction of the moving parts, in which case it is necessary to have a motor to start it, or it may fall by its own weight, in which case it will cause the motor to act as a generator, and the braking action of the motor armature in controlling the speed in lowering constitutes the chief feature of the Day control.

For hoisting it is usual to have the resistance in series with the armature both for starting and for speed control, but for lowering a load or carrying very light loads a different combination is made, so that the rheostat to which the controlling switch is connected, instead of being in series with the armature and gradually short-circuited as the armature is brought up to speed, is connected across the line in parallel with the armature.

The elementary connections are shown in Fig. 98.

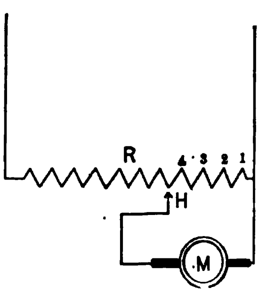


FIG. 98.—Day System of Control.

By this arrangement a small amount of current is taken from the line through the rheostat *R* while the armature is being operated, in addition to the current taken or given out by the armature itself, according as it is acting as a motor or as a generator.

On the first contact of the resistance, the rheostat is connected across the line and the armature is in parallel with a very small portion of the rheostat.

The portion of the rheostat between the armature terminals may be considered as being in parallel with the armature as far as current taken from the line is concerned, and in series with the armature as regards current produced by the armature itself.

If on lowering, and on the first contact of the resistance, the load does not start, the motor armature will receive a small current from the line through the rheostat and proportional to the difference of potential between the points on the resistance to which it is connected. If the armature does not now start, throw in more resistance in parallel with the armature, shown in Fig. 116, by moving H more to the left. This will allow more current to pass through the rheostat into the armature, or the difference of potential between the terminals will now be greater.

If, however, in the first instance, the load was sufficient to overhaul itself, it would cause the motor to act as a generator and current would be given out by the armature through the small portion of the resistance with which it is now considered as being in series. The load still overhauling, any further movement of H to the left would cause the motor to move faster, as it is now generating current through an increasing resistance. To slow in this case, it is only necessary to move the contact arm to the right, when the motor is generating current through a smaller resistance, when larger currents would flow, and as this energy is brought into existence by the falling load it would gradually slow down, until when the armature circuit is short-circuited, the powerful currents induced would act as a counter torque and bring the weight to rest.

Moving the contact arm to the left, the armature will be gradually brought to full speed, whether the motor is acting as a generator as has been shown, or whether it is taking current from the line.

In this way the speed can be controlled no matter whether the motor is really lowering the load or whether the load is driving the motor.

In the ordinary rheostatic control with the resistance in series with the armature, more resistance turned into the circuit will cause the armature to run faster when it is driven by its load and there is no way of reducing its speed below its full-load speed.

Panel Control.

The systems of control previously discussed have had to do with the different means of starting motors by means of variable resistances in series or in parallel with the main current, and the variation in speed caused by changes in the voltage impressed on the motor terminals by changes in this resistance.

In the Panel control, the usual starting resistance is used, but changes in speed are caused by changes in the field excitation.

Speed Regulation by Change of Field Excitation.

Suppose a motor with constant voltage applied to its terminals to run with a constant load. The motor will run at constant speed, the current being just sufficient to overcome all losses and the resistance due to its load. If the field current is lessened, the counter E. M. F. would decrease in the same proportion if the speed remained as before. This would allow a greater current to flow through the armature and the increased power due to the increased current would cause the motor to run faster, until the counter E. M. F. had increased to such a value that the power absorbed by the motor was sufficient to overcome the resistance of the load at the new speed.

This shows a *decrease in the field excitation, produces an increase in the speed,* and vice versa.

The regulation of speed in a shunt motor is easily attained by connecting a variable resistance in series with the shunt winding, and as the current is small, the waste of power, or heat loss, is not great. In many cases variation in speed is attained by putting resistance in series with the armature.

In a series motor, the field regulation is more economically carried out by connecting a variable resistance in a branch circuit in parallel with the series winding. The current round the series coils is then decreased by decreasing the variable resistance in the branch circuit, causing more current to pass through this branch resistance instead of around the series windings.

Speed Regulation by Change of Field Reluctance.

Reference to equation 5, page 240, will show that in any motor the speed of the armature varies directly as $\mathfrak{E}$, the voltage impressed on the brushes and inversely both as the number of conductors, Z, in the armature winding, and as the strength of the magnetic field, N, within which the armature rotates.

On page 140 it is shown that the strength of a magnetic field, the flux, varies directly as the strength of the field coils, CS, energizing the iron or steel, and inversely as the magnetic reluctance of the magnetic circuit. The magnetic reluctance of a magnetic circuit corresponds to the resistance of an electric circuit. The resistance of air to magnetic lines is great, while that of iron is very small and of steel, still smaller. The magnetic circuit in a motor starts in a field pole, crosses the air gap to the armature core, continues through the core to the next pole piece, again crosses the air gap and returns to its starting point by the second pole piece and motor frame. The greatest part of the magnetic reluctance is in the air gaps and any change in the length or area of the air gap produces almost proportional changes in the strength of the magnetic field. If the reluctance is increased, the flux is decreased and the armature will run at a correspondingly increased speed.

This principle is taken advantage of in the Reliance Adjustable Speed Motor. Both the armature and inner faces of the pole pieces are given a slight taper, and represent surfaces of truncated cones, one within the other. Any movement of either, parallel with the shaft, increases or decreases the distance between the surfaces corresponding with the air gap. The normal position of the armature is directly beneath the pole pieces and in this position the air gap is a minimum, the reluctance least, and the flux the greatest. By withdrawing the armature laterally, the air gap not only increases in length, but also decreases in area; that is, the area of the air gap no longer corresponds with the area of the inner face of each pole, as there is a smaller surface of the armature core now directly under the pole pieces. Both these effects increase the reluctance and pro-

duce a gradual decrease in the magnetic field, and consequently a gradual increase of speed.

As the armature is withdrawn into regions of weaker fields, ordinarily there would be a tendency to brush sparking, particularly if the operation was accompanied by a change of load. This sparking is due to excessive currents in the coils when they are short-circuited by the brushes and to the reversal of the current in the coil while its terminals are passing under the brush. In the Reliance Motor, at the instant of commutation, the coil enters a field opposed to the main field. This is produced by special commutating poles, interpoles, whose energizing turns are in series with the armature conductors. These interpoles are displaced in a direction towards which the armature is withdrawn. The result of this is, that at all positions of the armature, the commutating effect varies with the load, and as the armature is withdrawn to a region of weaker field, it comes more and more under the influence of the interpoles, giving increased commutating effect as the main magnetic flux decreases.

In another type of motor designed on the same principle, the length of air gap is increased by radially moving the pole pieces away from the armature, the pole pieces consisting of plungers within a magnetic shell which are actuated by hand wheels.

Problems on Motors.

1. A shunt motor has an armature resistance of .04 ohm and a shunt resistance of 20 ohms. A current of 36 amperes is supplied at an E. M. F. of 80 volts; the armature makes 1500 revs. a minute, giving a tangential pull of 44 lbs. at the surface of a pulley whose circumference is 18″. Find the loss by heat in the armature and field, the counter E. M. F., the current in the armature and shunt, and the efficiency (net).

$\mathfrak{E} = C_s r_s \qquad C_s = \frac{80}{20} = 4 \qquad C_a = 36 - 4 = 32,$

$\mathfrak{E} = E + C_a r_a \qquad$ or $E = 80 - (32 \times .04) = 78.72.$

$$\begin{array}{llr} \text{Watts lost in field} = & \mathfrak{E}C_s = 80 \times 4 = & 320 \\ \text{Watts lost in arm.} = & C_a^2 r_a = \overline{32}^2 \times .04 = & 40.96 \\ \text{Total loss} & = & \overline{360.96} \text{ watts.} \end{array}$$

$$\begin{array}{lllr} \text{Watts supplied} & = \mathfrak{E}C = & 80 \times 36 = & 2880 \text{ watts,} \\ \text{Watts developed} & = EC_a = & 78.72 \times 32 = & 2519.04 \text{ “} \\ \text{or loss} & & = & \overline{360.96} \text{ “} \end{array}$$

H. P. avail. $= \frac{1500 \times 3 \times 44}{2 \times 33000} = 3$ or $3 \times 746 = 2238$ watts.

$$\text{Net eff.} = \frac{2238}{2880} = 77.7\%.$$

2. In a shunt motor, resistance of field coils 50 ohms, of armature .2 ohm, total current entering 25 amperes, difference of potential 100 volts, H. P. as indicated by dynamometer 2.75, find the electrical, gross, and mechanical efficiencies. *Ans.* Gross eff. $= 87.7\%$.
Elec. eff. $= 93.5\%$.
Mechanical eff. $= 82\%$.

3. A shunt motor has a field resistance of 33⅓ ohms, and an armature resistance of .06 ohm. The difference of potential is 100 volts and the current 48 amperes. The radius of the pulley is 3″. The difference of the weights of a flexible band dynamometer is 63 lbs. and the number of revolutions is 1800 per minute. Required, the gross, electrical and commercial efficiencies, and the loss in heating the coils.

$C_s = \frac{\mathfrak{E}}{r} = \frac{100}{33\frac{1}{3}} = 3$ amperes,

$C_a = 48 - 3 = 45 \qquad \mathfrak{E} - E = C_a r_a,$

or $\qquad E = 100 - 45 \times .06 = 97.3.$

$$\begin{array}{lr} \text{Watts supplied} = \mathfrak{E}C = 100 \times 48 = & 4800, \\ \text{Watts utilized} = EC_a = 97.3 \times 45 = & 4378.5 \\ \text{Watts lost in heating} & \overline{421.5}. \end{array}$$

Total output $= \omega T$ where ω is the angular velocity and T the torque in ft.-lbs. $\omega = 2\pi n$.

$$\omega T \text{ in ft.-lbs.} = 2\pi n T \times 1.356 \text{ in watts,}$$

for 1 H. P. $=746$ watts and 1 ft.-lb. per sec. $=\frac{33000}{60}=550$ ft.-lbs.

or $\qquad$ 1 ft.-lb. per sec. $=\frac{746}{550}=1.356$ watts.

$\therefore$ output in watts $=2\times\frac{22}{7}\times\frac{1800}{60}\times 63\times\frac{1}{4}\times 1.356=4027.4.$

Gross eff. $=\frac{4378.5}{4800}=91.22\%$. $\qquad$ Elec. eff. $=\frac{4027.3}{4378.5}=92\%$.

$$\text{Commercial eff.}=\frac{4027.3}{4800}=83.9\%.$$

4. An electric motor, shunt, has an armature resistance of .055 ohm and field resistance of 32 ohms. When making 1400 revs. per minute the tangential pull on a pulley 7.6 cm. radius is 25 kilos. The current supplied to the motor at a voltage of 105 is 35 amperes. Calculate the counter E. M. F., the heating effect, and the gross and mechanical efficiencies.

Output $=\frac{2\pi nT}{10^7}$ watts, where T is the torque expressed in ergs, 1 watt being equal to 10^7 ergs per sec., or output in watts

$$=2\times\frac{22}{7}\times\frac{1400}{60}\times\frac{7.6\times 25\times 1000\times 981}{10^7}=2733.7$$

$7.6\times 25000=$ gr. cm. which multiplied by 981 gives ergs.

$C_a=\frac{\mathfrak{E}-E}{r_a}$ or $E=\mathfrak{E}-C_ar_a=105-31.72\times .055=103.255,$

$\mathfrak{E}=C_sr_s \qquad C_s=\frac{105}{32}=3.28 \qquad C_a=35-3.28=31.72,$

$$\begin{aligned}\mathfrak{E}C_a&=105\times 35=3675\text{ watts},\\ EC_a&=103.26\times 31.72=3275\ \text{"}\\ \text{Heating effect}&\qquad\qquad \overline{400}\ \text{"}\end{aligned}$$

Gross eff. $=\frac{3275}{3675}=89.125\%$. $\quad$ Mechanical eff. $=\frac{2733.7}{3675}=74.38\%$.

5. A Thompson-Houston motor has an armature resistance of .06 ohm and field resistance of 33⅓ ohms. While absorbing a current of 32 amperes at 102 volts, the armature made 1350 revs. per minute with a tangential pull of 60 lbs. on a pulley 6 inches in diameter. Calculate the heating effect and the mechanical energy delivered and the electrical energy supplied.

Ans. Heating effect = 362.36 watts.
Elec. energy supplied = 3264.00 "
Mech. energy delivered = 2876.6 "

6. A shunt motor connected to 110-volt mains, when unloaded, takes 3 amperes in the armature and runs at a speed of 997 revs. per minute. The armature resistance is .11 ohm. Calculate the resistance that must be connected in series with the armature to reduce its speed to 800 revs. per minute when the armature current is 50 amperes. *Ans.* .33 ohm.

7. In the preceding example, the shunt current was 2.6 amperes and at full load, 50 amperes, the actual speed was 980 revs. per minute. This machine is now driven as a generator at a speed of 980 revs. per minute and the field rheostat is adjusted to give the same field current as before. Find the terminal voltage of the generator when the armature current is 50 amperes, and the difference in the resistance of the field (field and rheostat) in the two cases when acting as a generator and as a motor.

If the field current remains the same and the speed as a motor and generator constant, the counter E. M. F. of the motor will be equal to the total E. M. F. as a generator.

$$\text{Counter E. M. F.} = 110 - C_a r_a = 110 - 50 \times .11 = 104.5$$

$$e \text{ as generator} = E - C_a r_a = 104.5 \times 50 \times .11 = 99 \text{ volts.}$$

$$\text{Resistance of field and rheostat as motor} = \frac{110}{2.6} = 42.3 \text{ ohms.}$$

$$\text{Resistance of field and rheostat as generator} = \frac{99}{2.6} = 38.1 \text{ ohms.}$$

8. A 110-volt shunt motor has a speed of 1200 revs. per minute. The resistance of the shunt field is 110 ohms. The constant stray loss due to friction, eddy currents, etc., is 250 watts. The armature resistance is .4 ohm. Find the value of the armature current for which the efficiency is a maximum and find this maximum efficiency.

NOTE.—The maximum efficiency occurs when the variable loss is equal to the constant loss. *Ans.* 30 amperes.
78.9%.

9. Assuming that the armature flux of example 6 is constant at all loads, find the value of the counter E. M. F. and speed for which the output is a maximum; the value of the output and the efficiency. The shunt current is 2.6 amperes.

NOTE.—Maximum output results when the motor has such a speed that the current is reduced to half what it would be if at rest.

$$\text{At rest } C_a = \frac{110}{.11} = 1000 \text{ amperes,}$$

$$\text{for maximum output } C_a = \frac{1000}{2} = 500 \text{ amperes,}$$

$$\mathfrak{E} - E = C_a r_a, \quad \text{or } E = 110 - 500 \times .11 = 55 \text{ volts,}$$

$$E = \frac{nZN}{10^8} \qquad 110 - 3 \times .11 = \frac{997NZ}{10^8}$$

$$\frac{NZ}{10^8} = \frac{109.67}{997} = .11,$$

$$110 - 50 \times .11 = \frac{nNZ}{10^8} = n \times .11, \quad \text{or } n = \frac{55}{.11} = 500 \text{ R. P. M.}$$

$$\text{Total input} = 110 \times 502.6 = 55286 \text{ watts.}$$

When unloaded, power absorbed $= C_aE = 3 \times 109.67 = 329$ watts, or 329 watts are expended without doing work.

Total output $= C_aE - 329 = 500 \times 55 - 329 = 27.171$ watts.

$$\text{Eff.} = \frac{27.171}{55.286} = 49.2\%.$$

10. A motor generator is built up of a motor and generator mounted on a common shaft. Characteristics of motor: drum wound armature with 65 complete coils, armature flux 8,000,000 lines; difference of potential at terminals 110 volts; resistance of armature .1 ohm, of shunt winding 44 ohms, external current 62.5 amperes. Characteristics of generator: long shunt compound wound; ring armature with 120 coils; armature flux 9,200,000 lines; resistance of armature .09 ohm, of series winding .11 ohm, of shunt winding 50 ohms; total external resistance 2 ohms. Calculate the current the generator will deliver.

Ans. 50 amperes.

CHAPTER XV.

PRINCIPLES OF ALTERNATING CURRENTS.

All electric generators induce alternating currents in their armature windings, due to the conductors passing alternately magnetic poles of opposite polarity; in which operation the E. M. F. induced by the cutting of the lines of force is reversed as the conductor passes from pole to pole. One of the chief differences between continuous and alternating current generators is in the method of

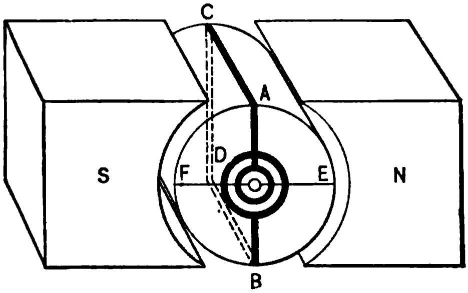


Fig. 99.—Coil in Magnetic Field.

collecting the current from the armature conductors; the continuous current generator requiring a commutator to rectify the alternating currents of the armature conductors into current in one direction in the external circuit, while in an alternator the currents are collected by rings and the currents in the external circuit are in the same direction as those in the armature conductors.

Variation of E. M. F.—A reference to Fig. 99 will show a rectangular coil *ABCD* at right angles to the magnetic field between the poles *N* and *S*.

The E. M. F. generated by a coil moving in a magnetic field is numerically equal to the *rate* at which it cuts the lines of force. The rate of cutting varies with the position of the coil as it moves around its center of revolution *O*. It must be remembered that

the active cutting portions of the coil are AC and BD, the remaining portions CD and AB simply completing the closed circuit.

In the position of the coil shown by AB, the rate of cutting of lines of force is least, as at that position, the motion of the conductor AC is parallel to the lines of force, but in a position 90° from AB, as at EF, the rate of cutting is greatest, as at this position, the motion of the conductor is perpendicular to the lines of force.

If V represents the velocity of the coil in its revolution, the velocity at any instant is the linear velocity in a tangent to the circle of revolution at that point. In Fig. 99 the velocity at the point E is represented by the velocity in the tangent at that point, V, shown in Fig. 100. As the generated E. M. F. is greatest at that point, the maximum E. M. F. may also be represented by V, for the E. M. F. is numerically equal to the velocity, or rate of cutting. The rate of cutting at any point is proportional to the component of V that is perpendicular to the lines of force, that is, the vertical component, and at any point H, the vertical component is $V \cos \theta'$, or $V \sin \theta$, where θ is the angle turned through from the initial or zero position, and therefore, the E. M. F. at any point is equal to $V \sin \theta$, where V is the maximum E. M. F.

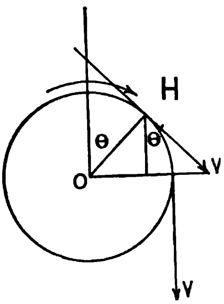


FIG. 100.

A curve of variation of E. M. F. is shown in Fig. 101, where for each value of θ measured horizontally in degrees from 0°, ordinates are set up vertically to represent $V \sin \theta$, the E. M. F. for that position of the conductor, and a curve drawn through the points so obtained.

This is a **sine curve** and the change of direction of the E. M. F. which occurs when the conductor begins to cut the lines in the reverse direction is shown by the curve crossing the zero line. E. M. F's. above the line are called *positive* and those below *negative*.

Definitions.—The time taken by the E. M. F. to pass through a complete series of changes such as represented in Fig. 101 is called a **period**, and the complete operation is called a **cycle**.

The **frequency** is the number of periods, or number of cycles per second.

The **amplitude** is the maximum value of the variable E. M. F.

The **phase** of any point is measured by the angle swept over by the point from the zero position. Thus the phase at position of maximum positive E. M. F. is 90°, maximum negative E. M. F. is 270°, at minimum E. M. F. it is 0°, 180° or 360°. The phase may also be measured in terms of a complete cycle, thus the phase at 90° is $\frac{1}{4}$, at 180° is $\frac{1}{2}$, at 360° is 1, etc.

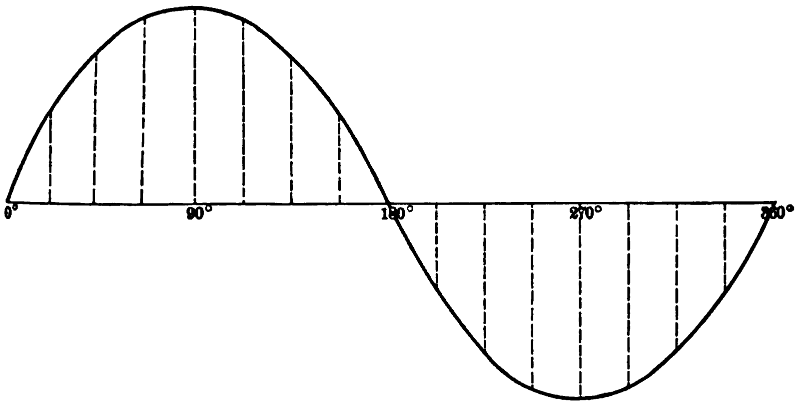


FIG. 101.—Curve of E. M. F.

Example.

A bipolar alternator gives a maximum of 500 volts with a frequency of 100, what will be the phase and voltage $3\frac{1}{3}$ seconds after starting from the point of minimum E. M. F.?

In $3\frac{1}{3}$ seconds, a coil will have passed through $3\frac{1}{3} \times 100 \times 360$ degrees, or 333 complete cycles and $\frac{1}{3}$ of a cycle, and the coil will be in phase $360° \div 3 = 120°$.

The value of the E. M. F. at phase 120° will be $V \sin \theta$ or $500 \times \sin 120° = 433$ volts.

Effect of Increase in Number of Poles and Conductors.—The frequency of the alternations depends upon both the speed with which the conductors are moved and upon the number of the alternate poles under which the alternations take place. In the case of

a multipolar machine a period will be the time occupied for a conductor to move from one pole to a similar position under the nearest pole of the same polarity. In a 10-pole alternator there will be five periods per revolution, or the frequency per revolution will be five. In general, if

n = number of revolutions per minute,
P = number of pairs of poles,
n' = frequency.

Then
$$n' = \frac{n \times P}{60}.$$

In order to increase the E. M. F. generated in a machine, the number of conductors must be increased, and the total E. M. F. generated in an armature composed of a great number of conductors will be equal to the sum of the voltages in the individual conductors if (1) *the conductors under opposite poles are joined alternately at the front and back of the armature so that the E. M. F. induced in the successive conductors in opposite directions is made to act in the same sequence in the complete winding,* and (2) *if the conductors passing under a pole at any time are sufficiently close together to enter and leave the pole at nearly the same time.*

Self-Induction in an Alternating Current.

An alternating current is always accompanied by a *changing* magnetic field, the rapidity of the change being dependent on the number of the alternations. This rapidly changing field reacts on the current producing it, and has the same effect as though the conductor were moved through a field of as many lines of force as are produced by the current. The effect of the changing field on the conductor is to generate an E. M. F. called the *E. M. F. of self-induction,* which acts to oppose any change in the current. If the current is increasing, this self-induction tends to oppose the increase and if decreasing, it opposes the decrease.

This E. M. F. of self-induction, sometimes called *back* or *counter* E. M. F. is dependent on the rate at which the magnetic field due to the current changes, and hence is proportional to the rate at which the current itself changes and not directly on the current or on the number of lines of force.

Curves of Current and Rate of Change of Current.—Fig. 199 shows that the induced E. M. F. in an alternating current and consequently the current produced thereby is proportional to the sine of the angle through which the conductor has moved, and consequently the rate of change of current is proportional to the differential of the sine or is equal to the cosine of the angle in radians. Fig. 102 shows curve *I* plotted as a **current curve,** and *II,* **a rate of change of current curve.**

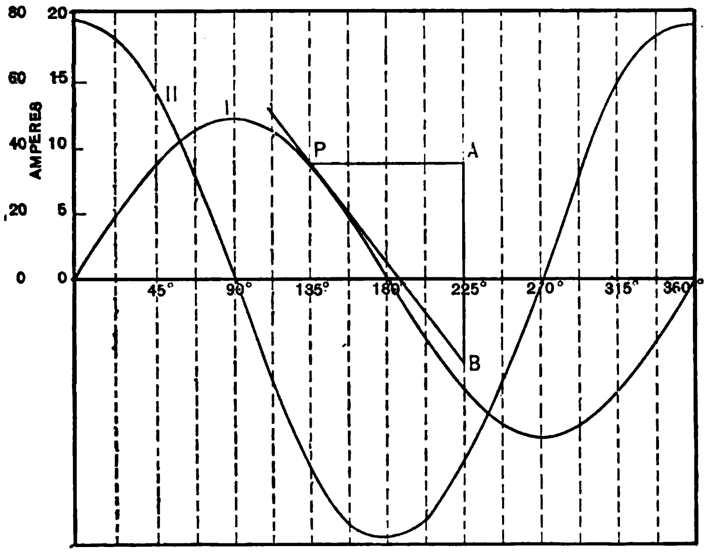


FIG. 102.—Curves of Current and Rate of Change of Current.

Curve *I* is plotted from the equation $y = C \sin x$. Curve *II* is plotted from the rate of change of curve *I*. The rate of change of the sine of an angle is equal to its cosine when measured in radians. As there are 2π radians in 360° or one cycle, the rate of change per cycle is 2π times the cosine of the angle. The equation for plotting curve *II* then becomes $y' = 2\pi C \cos x$, and the ordinates are plotted as currents and the abscissæ as angles. The maximum value of the rate of change of current occurs when $x = 0°$, for then $y = 2\pi C$ and the maximum ordinate is 6.3 times

the maximum value of C. In the example chosen, the maximum value of C is 12 amperes, and the maximum value of the rate of change of current is $6.3 \times 12 = 75.6$ amperes. For convenience in plotting, the scale of curve *II* is taken four times as great as curve *I*.

It will be noticed that the minimum value of the rate of change of current occurs when $x = 90°$, for then $y' = 2\pi \cos 90° = 0$. The above considerations show that the curve of rate of change of current differs in phase by $\frac{1}{4}$ of a period from the current curve, and that it is in advance in phase by that amount.

Curve *II* could be geometrically plotted as follows: From any point P on the current curve draw a tangent PB and from P lay off a horizontal distance PA equal to the length of $\frac{1}{4}$ cycle and draw a vertical line from A till it meets the tangent at B, then the distance AB is the ordinate on the rate of change of current curve for $\frac{1}{4}$ cycle; and for a curve for a whole cycle, such as *II*, the ordinate would be a distance four times as great. This ordinate would be a point on curve *II* corresponding to the phase of the point P.

If the current passes through n cycles per second, the maximum value of the rate of change per second is $2\pi nC$.

The **coefficient of self-induction** is equal to the E. M. F. induced by a change of one ampere per second, and if

E = E. M. F. of self-induction
L = coefficient of self-induction

we may write, when the current is changing at the rate of one ampere per second

$$E = L.$$

If the ordinates of curve *II* are multiplied by n, it would be a curve of $2\pi nC$, and if the current changes at the rate of $2\pi nC$ amperes per second, the induced E. M. F. of self-induction is

$$E = 2\pi nCL. \qquad \text{(a)}$$

From a consideration of the above it is shown that when an alternating current is flowing, it gives rise to a back E. M. F. opposing the change of current, and to overcome this back E. M. F. an additional E. M. F. determined by equation (a) must be applied.

However, from the fact that the two curves of E. M. F. differ in phase, not all of the E found from equation (a) is necessary, but it offers a means of determining what the real applied E. M. F. must be in order to produce a certain current.

Curve of Applied E. M. F.

Suppose it is required to find the applied E. M. F. necessary to maintain a maximum current of 10 amperes in a resistance of 1.5 ohms in a circuit with a self-induction of .005 henry. The alternator has 12 poles with a speed of 1200 revolutions per minute.

There are now two E. M. F's. to be considered: first, that necessary to supply 10 amperes in a resistance of 1.5 ohms, which is the same E. M. F. that would be required in a continuous current; and, second, that necessary to overcome the back E. M. F. due to self-induction. The current curve as plotted is marked C in Fig. 103.

The *resistance E. M. F.*, as it is called, can be plotted to any convenient scale, by multiplying the values of the current at any instant by the resistance of the circuit. Thus the maximum value of the resistance E. M. F. is, for the example cited, $10 \times 1.5 = 15$ volts. This is shown plotted as a curve of sines in Fig. 103, marked E_1.

The curve due to the change of current, or, what is the same thing, the curve of back or *inductance E. M. F.* can now be plotted on the same scale, from the equation $E = 2\pi nLC$, remembering that the curve of inductance E. M. F. is $\frac{1}{4}$ period in advance of the curve of resistance E. M. F.

The frequency is $\frac{12}{2} \times \frac{1200}{60} = 120$, and the maximum value of E is $2\pi \times 120 \times .005 \times 10 = 37.7$ volts.

The alternator must supply a voltage equivalent to both of the E. M. F's. if the condition required is to be maintained, and at any instant, the applied E. M. F. must be equal to the sum of the resistance and inductance E. M. F's. at that instant. Curve E_3 is plotted by adding together *algebraically* the ordinates of the two curves E_1 and E_2. In the example, the greater portion of the applied E. M. F. is needed to overcome the inductance, but where the inductance is small, the greater part might be necessary to overcome the resistance.

It is seen that the required E. M. F. is not the arithmetical sum of the two E. M. F's. arising from the fact that the two E. M. F's. are not in the same phase.

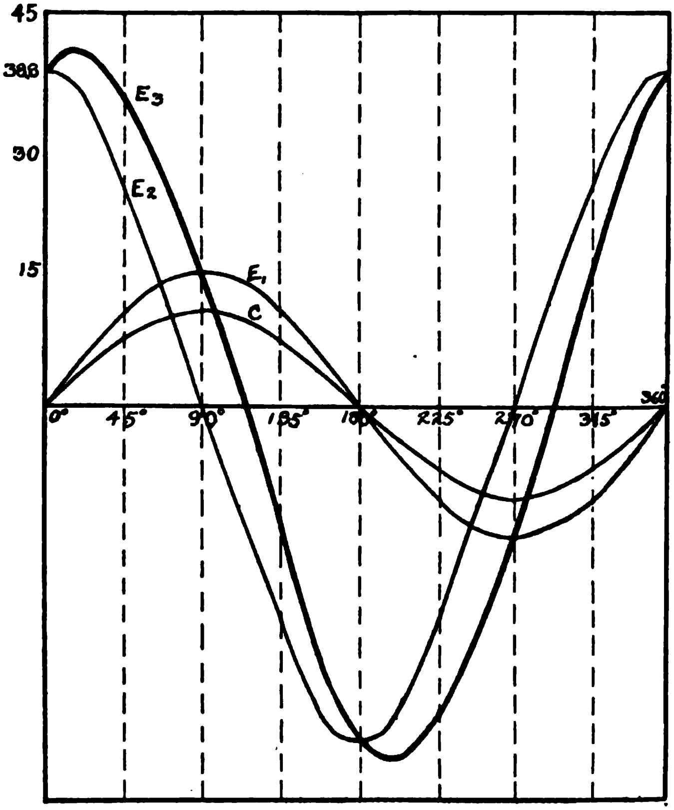


FIG. 103.—Curves of E. M. F. and Resultant E. M. F.

Angle of Lag and Lead.—It will be noted that the curves E_3 and C are not in phase with one another, the difference in phase being measured on the horizontal scale between the points at which they pass through their zero values. If the current curve passes through its zero value at an angle greater than the total E. M. F. curve does, the current is said to *lag* by an amount equal to the

angle of lag, and if the opposite is the case, the current is said to *lead* by an amount equal to the **angle of lead.** Inductance always causes an angle of lag which depends on the nature of the resistances and other apparatus in circuit.

Graphic Representation of Alternating Currents.

The two curves, C and E_3, in Fig. 103, show the changes undergone by the applied E. M. F. and resulting current in one cycle, or in one alternation, and for any given value of E. M. F. the resulting current can be found. From the fact that the two curves differ in phase, the maximum current does not occur at the same time as the maximum E. M. F. To find the current corresponding to maximum E. M. F. it is only necessary to draw an ordinate through the position of maximum E. M. F. and the portion of this ordinate common to the current curve will be the desired value. Thus, in Fig. 103, the desired current is about 5.5 amperes.

Although the varying E. M. F's. and currents can be well represented by curves, such as shown in Fig. 103, yet the process of plotting is tedious, and another method of plotting by right lines, called **vector diagrams,** and which will show all the varying quantities, has been devised.

As the resistance E. M. F. and inductance E. M. F. differ in phase by $\frac{1}{4}$ of a period, or are 90° apart, they may be represented by straight lines at right angles to each other, the lines by their length representing the values of the E. M. F's. If the triangle is completed by drawing the hypothenuse, this will represent by its length the value of the resultant E. M. F. These values will give the maximum value of these quantities. To show the varying values of these quantities it is only necessary to project their lengths on a straight line suitably placed. Such an arrangement is shown in Fig. 104.

From O is drawn to scale OE_2 in any direction, the maximum value of the inductance E. M. F. and equal to $2\pi nCL$, and from E_2 and at right angles to OE_2 is drawn E_1E_2, the maximum value of the resistance E. M. F. and equal to CR. Then the hypothenuse OE_3 is drawn and it will represent, according to the scale adopted, the maximum value of the resultant E. M. F., and equal to $C\sqrt{R^2 + (2\pi nL)^2}$.

The instantaneous values of the E. M. F's. are found by projecting $E_1E_2E_3$ on the horizontal line ON, where the distances OA, OB, BA measured to scale will be the instantaneous values at any instant when the whole triangle is revolved about O. The instantaneous value of the resultant E. M. F. is the sum of the instantaneous values of the component E. M. F's. Thus the instantaneous value of E_2 is OA, of E_1 is AB (negative) and of E_3 is OB, which is the sum of $OA + (-AB)$. As the triangle is revolved about O, the instantaneous values of the variable quantities may be obtained at any instant. When the line OE_2 is on the line ON, the

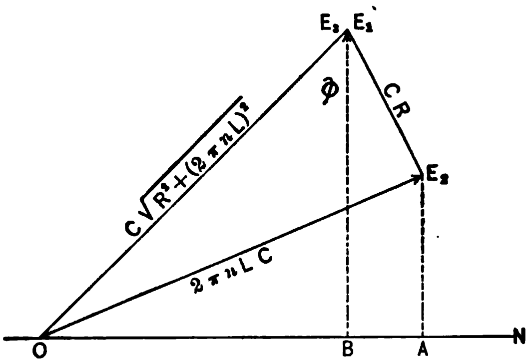


FIG. 104.—Component and Resultant E. M. F's.

projection of E_1 is zero, and E_2 is a maximum as previously seen in Fig. 103.

The angle between the two vectors representing the curves E_1 and E_3 is the phase, represented by ϕ in the figure.

Magnitude of Resultant E. M. F.—In Fig. 104 it is shown how the resultant E. M. F. may be obtained when the component E. M. F's. are known, and as this is the hypothenuse of a right triangle, the value of the resultant E. M. F. can readily be calculated.

$$OE_3^2 = OE_2^2 + E_1E_2^2,$$

or

$$V^2 = (2\pi nCL)^2 + C^2R^2,$$

and

$$V = C\sqrt{R^2 + (2\pi nL)^2}.$$

Of this value V, CR is spent in overcoming the resistance of the

circuit, and $C2\pi nL$ in overcoming the back E. M. F. of self-induction. If there is no self-induction $L = O$, when $V = CR$, in accordance with Ohm's law.

Impedance.—It has been shown above that the current in an alternating circuit cannot be calculated by Ohm's law, owing to the effects of self-induction, and it acts as though the resistance instead of being R was increased to $\sqrt{R^2 + (2\pi nL)^2}$. The current is not generally governed by the resistance but by the inductance. In Ohm's law, the voltage divided by current gives the resistance, but in alternating currents, the voltage divided by current gives a factor, represented by $\sqrt{R^2 + (2\pi nL)^2}$, which is called the **impedance.**

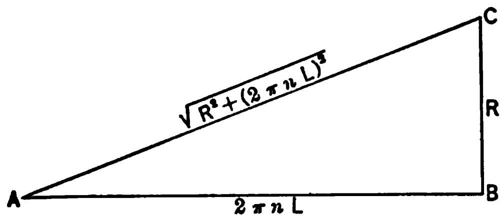


FIG. 105.—Triangle of Resistance and Impedance.

Fig. 104 shows that each side of the triangle of E. M. F's. contains the current factor C, and if each side be divided by C, there will remain a triangle which can be plotted to a scale of resistance. These three sides are represented in Fig. 105.

The side of the triangle $BC =$ resistance $= R$,

$$AC = \text{impedance} = \sqrt{R^2 + (2n\pi L)^2},$$
$$AB = \text{reactance} = 2\pi nL.$$

If R is small, the impedance becomes practically the reactance and if the inductance is small, the impedance becomes nearly equal to the resistance.

From a consideration of the factors entering into the formula representing the impedance, it is seen that it depends upon the ohmic resistance R, the inductance L, and the speed, or frequency, n. The resistance is independent of frequency, whereas the reactance depends directly on the frequency.

Capacity in an Alternating Circuit.

All conductors possess a certain amount of capacity depending on their form and their nearness to other conductors. This capacity of insulated conductors is so small that it does not prevent the current flowing from obeying Ohm's law; but if the circuit possesses electrostatic capacity given by some form of condenser, a *charging current* will have to flow first into the condenser before the voltage acting on the resistance of the circuit can attain the full value of the applied E. M. F.

In the case of an alternating current, there is a charging current at each reversal of E. M. F., and the total current is the sum of the charging current and the normal current following Ohm's law. As soon as a condenser is charged to full potential, the flow of current will cease until the voltage of the applied current changes. A condenser in a continuous current circuit thus stops all flow of current, but in an alternating current, the potential is continually changing, and the current flows into and out of the condenser, changing its sign.

If $Q =$ quantity of electricity in coulombs
$K =$ capacity of a condenser
and $E =$ difference of potential between terminals of the condenser.

Then $Q = KE$, and a *conductor has unit capacity, one farad, when it is raised to unit voltage, one volt, by one coulomb of electricity.*

The current flowing into a condenser is equal to the rate of change of the charge.

The current is the rate at which quantity of electricity flows, and the charging current will be the rate of change of quantity, or rate of change of KE, and will be equal to the current flowing into the condenser. This charging current, or the current flowing into the condenser, is

$$\frac{Q}{t}, \text{ and since } Q = KE, \frac{Q}{t} = \frac{KE}{t}, \text{ or}$$

the charging current is equal to the capacity times the rate of change of voltage at the terminals.

The relation between charging current and the applied voltage

may be graphically shown as in the case of the current curve and the rate of change due to self-induction shown in Fig. 102.

In Fig. 106, is plotted curve *I* for a maximum E. M. F. of 12 volts, and its rate of change is shown in curve *II*. For convenience in plotting, this curve is plotted for one radian, and the maximum value for one cycle would be $2\pi \times 12$ volts, and for a frequency of n per second, it would be $2\pi n \times 12$ volts.

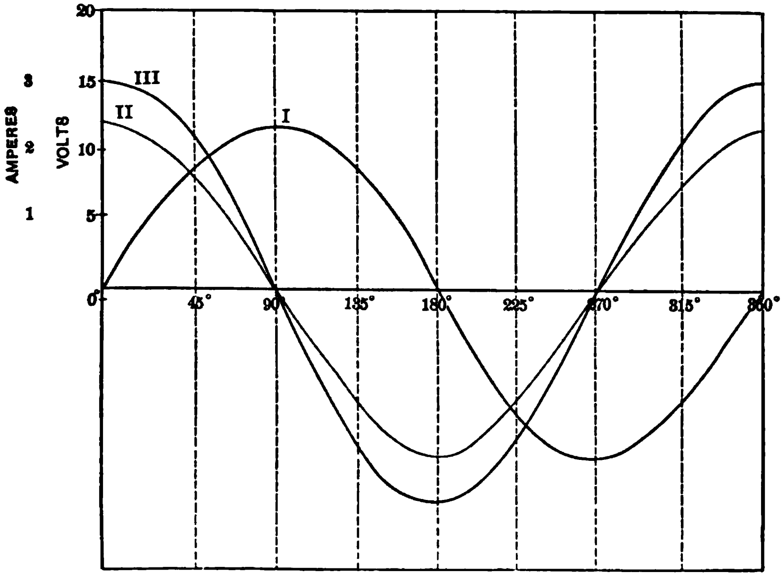


FIG. 106.—Curves of E. M. F. and Charging Current.

If the circuit had a capacity of 400 microfarads and a frequency of 100, the capacity factor would be

$$2\pi nK, \text{ or } \frac{2 \times 3.14 \times 100 \times 400}{1{,}000{,}000} = .25.$$

Since $\frac{Q}{t} = \frac{KE}{t}$, to find the ordinate of the charging current, each ordinate of $\frac{E}{t}$, the rate of change of E. M. F., or curve *II*, must be multiplied by .25. The maximum value is $.25 \times 12 = 3$ amperes, which is plotted as curve *III* on a second scale of amperes.

An inspection of Fig. 106 shows that the charging current differs in phase from the E. M. F. and is always *one-quarter of a period in advance,* and the effect of introducing capacity in an alternating current is to cause the current to **lead,** being just opposite to the effect caused by induction. In addition to this charging current, which is out of phase with the E. M. F., there is the current due to the resistance of the circuit and which is in phase with the E. M. F. This curve of current could be plotted on the same diagram by dividing the ordinates of the voltage curve by the resistance, and the *total* resulting current curve could then be found by adding algebraically the ordinates of the charging and resistance currents, exactly as in the case of finding the resultant curve of E. M. F. in Fig. 103.

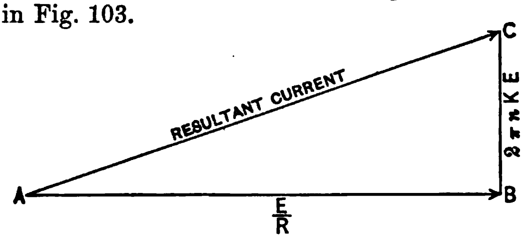


FIG. 107.—Vector Diagram of Currents.

Vector Diagrams.—Similar to the case of resultant E. M. F. the resultant current may be found by vectors, one drawn to scale to represent the resistance current, and another at right angles to represent the charging current, when the hypothenuse will represent the resultant current according to the scale adopted. The resistance current is in phase with the E. M. F. and the angle between this vector and the resultant current vector will be the angle of *lead.* Such a drawing is represented in Fig. 107.

Impedance Due to Capacity.—The impedance, as shown under induction, is equal to the E. M. F. divided by the current, and therefore the resistances of the vectors in Fig. 107 may be obtained by dividing the E. M. F. by the respective currents. Thus, for *AB,* the resistance is

$$E \div \frac{E}{R} = R,$$

and for *BC,* the resistance is

$$E \div 2\pi nKE = \frac{1}{2\pi nK}.$$

A similar diagram may now be drawn for the resistances as in Fig. 108, from which the impedance may be found.

The impedance is $\sqrt{AC^2} = \sqrt{AB^2 + CB^2} = \sqrt{R^2 + \left(\frac{1}{2\pi nK}\right)^2}$.

The current in an alternating circuit depends upon the resistance, and capacity in circuit and the frequency of the alternations.

Impedance Due to Induction and Capacity.—Since induction produces lag and capacity, lead, when these two are connected in series, their effects are opposed and the combined effect of the impedance is given by the formula

$$\sqrt{R^2 + \left(2\pi nL - \frac{1}{2\pi nK}\right)^2}$$

and the expression for the resultant current is

$$C = \frac{E}{\sqrt{R^2 + \left(2\pi nL - \frac{1}{2\pi nK}\right)^2}}.$$

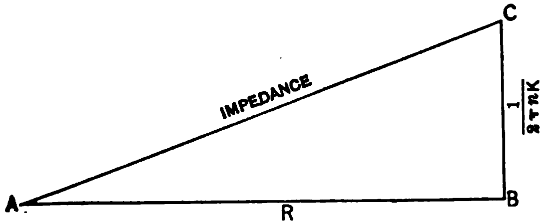


FIG. 108.—Resistance Diagram.

Power.

The power of an alternating circuit, like that of a continuous current, is the product of the E. M. F. and current. This is true for any part of the circuit under consideration, and for any part of an alternating circuit, the power developed is numerically equal to the product of the current flowing in the portion considered and the difference of potential between the two points of the circuit. In the case of alternating currents, as the current and E. M. F. are not in phase, they may be acting in opposite directions, in which case their product must be considered negative.

When the power is negative the circuit is not receiving power from the source of supply, but is giving back power to assist in driving the generator of the currents. As energy is equal to power times time, the energy actually given to any external circuit is equal to the arithmetical sum of the power of the circuit multiplied by the time.

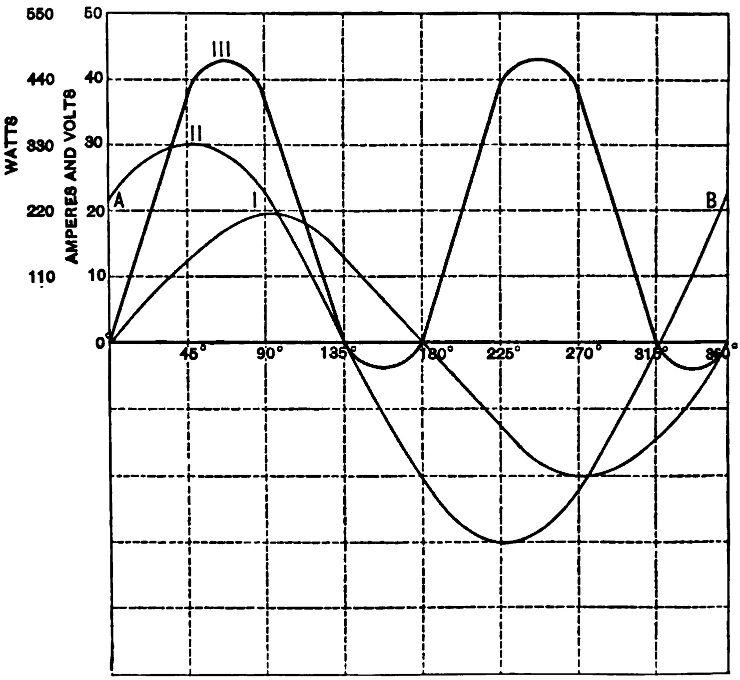


FIG. 109.—E. M. F. Current and Power Curves.

The average power given to an external circuit is the *average* value of the product of volts and amperes. The effect of negative power is shown in Fig. 109 where are plotted curves of E. M. F. and current, from which is plotted a third curve, the watt curve, from values found by the product of volts and amperes for the same instant. Curve *I* represents the resultant current due to a resultant E. M. F. shown in curve *II*, the voltage leading the

current by a phase of 45°. If for any instant, the product of the instantaneous values of E. M. F. and current be found, it will give the power developed in the point of the circuit under consideration. If a number of points be so determined for a cycle, a curve drawn through these points will represent the power or **watt curve**, and curve *III* has been so determined. It must be remembered that all points above the horizontal zero line are to be reckoned as *positive* and those below as *negative*, and the product of two positive quantities or two negative quantities will be positive, while the product of a positive and negative quantity will be *negative*. Thus, all the products will be positive except between 135° and 180°, and between 315° and 360° which will be negative. The curve is roughly plotted to the scale of watts shown on the left-hand side of the diagram.

The **average power** developed in the circuit is the average value of the product of volts times amperes in the circuit. This is found by adding together ordinates of the watt curve and dividing by the number taken. Ordinates below the zero line must be subtracted from those above. The average power is shown in the figure by the dotted line *AB*.

This average power is that indicated by a wattmeter. The readings of a voltmeter and ammeter connected in circuit will not give the true average power by taking their product, for their readings are given independent of the phase of the voltage and current. If these are in phase the product of the volts and amperes as shown by the instruments should be the same as that indicated by a wattmeter, but not otherwise.

If the current and voltage were in phase, there would be no negative power and the average power would be greater, but as the phase difference increases up to 90°, the negative power increases and the positive decreases, and at 90° they would be equal, or the average power given to the circuit would be zero, or the current would be *wattless*. A wattmeter under such condition would indicate zero, while the voltmeter and ammeter would indicate as though the phase was zero, as they would under all conditions of phase.

The product of the voltmeter and ammeter readings gives the *apparent watts*.

The **power factor** is the ratio of the true watts to the apparent watts, or

$$\text{power factor} = \frac{\text{true watts}}{\text{volts} \times \text{amperes}}$$

or true power = volts $\times$ amperes $\times$ power factor.

The resultant E. M. F. consists of two components, one in phase with the current and one differing in phase by one-quarter of a period. When the resultant E. M. F. differs in phase from the current, by one-quarter of a period, the average power is zero. One component of the E. M. F. therefore does not affect the power of the circuit, and is called the **idle E. M. F.** while the other component multiplied by the current gives the total power, and this component is called the **energy E. M. F.**

The components, energy and idle E. M. F's. are at right angles to each other, the hypothenuse being the total E. M. F., and the phase is the angle between the energy E. M. F. and total E. M. F.

If E is the total E. M. F. the power given out is $C \times$ energy E. M. F. $= C \times E \cos \phi$, where ϕ is the phase.

As the power given out $= C \times E \times$ power factor, it follows that the *power factor is equal to the cosine of the angle of phase.*

Comparison of Values of Direct and Alternating Currents.

In order to compare direct and alternating currents, it is necessary to compare effects which are independent of the direction of the current, and such a comparison is found in their heating effects when passed through resistances.

A direct current of C amperes flowing through a resistance R will develop C^2R joules per second, and an alternating current of equivalent value will also develop the same number of joules per second in the same resistance. Hence the average value of C^2 alternating must equal the average value of C^2 direct. The average value of the square root of C^2 direct is C, but the average value of the square root of C^2 alternating is not the same as the average value of C alternating.

The average value of the ordinates of the sine curve is $\frac{2}{\pi} = .635$,

but the square root of the squares of the ordinates = .707 of the maximum height, or $\frac{1}{\sqrt{2}}$ times the maximum value.

The average value of an alternating current is not used, but rather the alternating current which is *equivalent* to a direct current. This last is called the **virtual** current and is equal to the square root of the average value of the squares, and it is this value which is registered on an ammeter and the one used in designating the strength of an alternating current.

The same remarks apply to an alternating E. M. F. and the virtual volts are those shown on a voltmeter. If a voltmeter showed 70.7 volts, the maximum voltage would be 100 volts and if an ammeter showed 100 amperes, it would mean that the current was varying between 0 and 141 amperes.

Most voltmeters and ammeters for measuring alternating currents give readings proportional to the mean values of the square of current or voltage, and if they are designed so that the deflection is proportional to the deflecting force, the division of the scale marks are uneven, as the distance between marks increases in the ratio of the square of the value being measured.

Average Power.—The average value of C^2R in an alternating circuit is one-half the maximum value. The maximum value of the power is equal to the product of maximum volts and maximum amperes, and the average power is $\frac{1}{2}$ (maximum volts times maximum amperes) or $\frac{1}{\sqrt{2}}$ maximum volts times $\frac{1}{\sqrt{2}}$ maximum amperes. These last factors are the virtual values, or

average power = virtual volts times virtual amperes.

It is the *average* value of the watts which gives the true power in a circuit, and this can be found by taking the product of the virtual volts and virtual amperes as shown by the instruments, *if the E. M. F. and current are in phase.* If not in phase, the average value of the power is $\frac{1}{2}$ $CE \cos \phi$, where C and E are maximum values and ϕ the angle of phase.

Series Circuits.

Reproducing the vector triangle involving resistance and inductive reactance, we have Fig. 110, $2\pi r$ being represented by ω. Inductance causes the current to lag behind the impressed E. M. F. The direction of R represents the phase line of the current and the

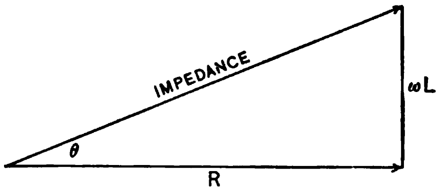


FIG. 110.—Vector Triangle of Resistance and Inductive Reactance.

direction of impedance the phase line of the E. M. F., angle θ being the angle of lag, and is determined by

$$\theta = \tan^{-1}\frac{L}{R}.$$

The vector triangle involving resistance and condensive reactance is shown in Fig. 111. Condensive reactance causes the current to

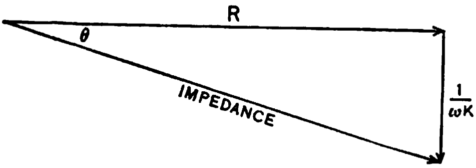


FIG. 111.—Vector Triangle of Resistance and Condensive Reactance.

lead the E. M. F., and in the figure is shown by angle θ, whose value is

$$\theta = \tan^{-1}\frac{\frac{1}{\omega K}}{R}.$$

The angle of lag or lead is determined by the preponderance of the inductive or condensive reactance, and the vector diagram of a circuit containing resistance and both inductive and condensive reactance is shown in Fig. 112.

The phase angle is θ and in the case shown the angle of lag is

$$\theta = \tan^{-1} \frac{\omega L - \frac{1}{\omega K}}{R};$$

and if the value of θ is negative, or $\frac{1}{\omega K}$ has a greater value than ωL, θ is the angle of lead.

In alternating current circuits containing resistances, inductances and capacities, or any combination of these units, in which all are joined in series, the relation between the impressed E. M. F. and the resulting current can be obtained from a consideration of the following:

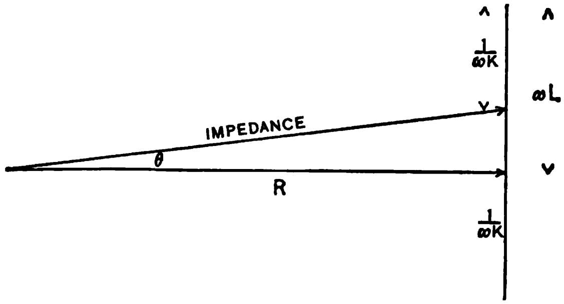


FIG. 112.—Vector Triangle of Resistance and Inductance and Condensive Reactance.

The **total resistance** in circuit is the **arithmetic** sum of the separate resistances; the **total inductive reactance** is equal to the **arithmetic** sum of the separate inductive reactances; the **total condensive reactance** is the **arithmetic** sum of the separate condensive reactances; the **total reactance** is the **algebraic** sum of the inductive and condensive reactances, and the **total impedance** is the **geometric or vector** sum of the total reactance and the total resistance.

The relation between the E. M. F. and resulting current is given by the expression

$$C = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega K}\right)^2}},$$

where R is the total resistance, L the combined inductance and K the combined capacity.

A series circuit is shown in Fig. 113, where are illustrated two resistances, $r_3 r_4$, two inductances, $L_1 L_2$, and two capacities, $K_1 K_2$, all connected in series to a source of E. M. F. In addition L_1 and L_2 have ohmic resistance represented by r_1 and r_2.

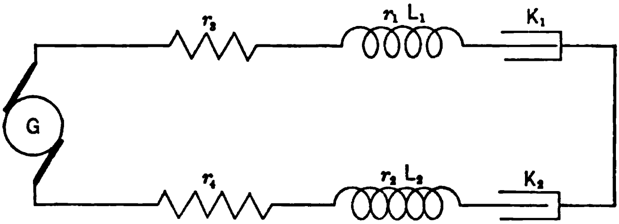


FIG. 113.—Series Alternating Current Circuit.

The total resistance $R = r_1 + r_2 + r_3 + r_4$.
The total inductive reactance $\omega L = \omega L_1 + \omega L_2$.

The total condensive reactance $\frac{1}{\omega K} = \frac{1}{\omega K_1} + \frac{1}{\omega K_2}$.

The total reactance $= \omega L - \frac{1}{\omega K}$.

The total impedance $= \sqrt{R^2 + \left(\omega L - \frac{1}{\omega K}\right)^2}$.

The total current $C = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega K}\right)^2}}$.

Problems involving pure series connections may be solved from the formulæ given above or by the vector diagram, preferably by the formulæ, but the vector diagram is given as an illustration of the method used.

In Fig. 114 OA is drawn to scale to represent the sum of the resistances r_1 and r_3, and AB to represent the sum of the resistances r_2 and r_4, or OB could be drawn at once to scale to represent the total R.

OC is drawn to the same scale as OB to represent the inductive reactance ωL_1 and CG to represent ωL_2, the arithmetic sum of which is OG.

CD is laid off from C equal to the condensive reactance $1/\omega K$, and GH from G equal to $1/\omega K_2$, and the arithmetic sum of CD and GH is equal to GF.

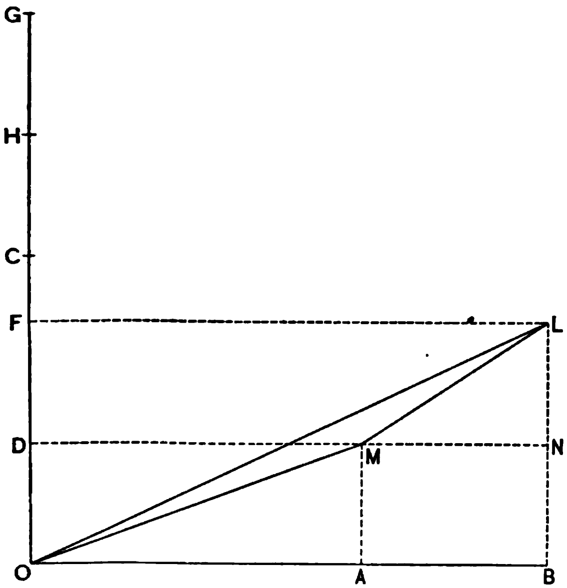


FIG. 114.—Vector Diagram of Series Circuit.

The total reactance is $(OC + CG)—(CD + GH)$ or $OG — GF = OF$.

The total impedance OL is then obtained by taking the geometric sum of OB and OF, which is OL.

This can be similarly obtained by finding the impedance due to one set of resistances and one of the inductive and condensive reactances together, and the impedance due to the other set of resistances and to the other inductive and condensive reactances taken

together, and then finding the geometric sum of these two impedances. Thus, combining the inductive reactance *OC* with the condensive reactance *CD* gives *OD*, which combined geometrically with *OA*, gives *OM*, one impedance. Combining the inductive reactance *CG* with the condensive reactance *GH*, gives *HC*, which laid off from *D* gives *DF*. This reactance *DF* or *LN* combined with *AB* or *MN* gives *LM*, a second impedance. Adding geometrically the two impedances *OM* and *ML* gives the total impedance *OL*.

Example.—Suppose the factors shown in Fig. 113 had the following values:

$r_3 = 25$ ohms, $r_1 = 60$ ohms, $r_4 = 10$ ohms, $r_2 = 130$ ohms;
$L_1 = .25$ henry, $L_2 = .3$ henry, $K_1 = 18$ m. f., $K_2 = 25$ m. f.

It is required to determine the impressed E. M. F. necessary to send 10 amperes through the circuit, with a frequency of 60.

$$R = r_3 + r_1 + r_2 + r_4 = 225.$$

$$\omega L_1 = 377 \times .25 = 94.2.$$

$$\omega L_2 = 377 \times .3 = 113.1.$$

$$\omega L = 94.2 + 113.1 = 207.3.$$

$$\frac{1}{\omega K_1} = \frac{1,000,000}{377 \times 18} = 147.3.$$

$$\frac{1}{\omega K_2} = \frac{1,000,000}{377 \times 25} = 106.2.$$

$$\frac{1}{\omega K} = 147.3 + 106.2 = 253.5.$$

$$E = 10\sqrt{225^2 + (207.3 - 253.5)^2} = 2296 \text{ volts}.$$

The above calculation shows that the resistances could be replaced by an equivalent resistance of 225 ohms; the inductance by an equivalent inductance of 207.3 ohms; and the total reactance by an equivalent condensive reactance of 46.2 ohms, and that the current leads the E. M. F. by an angle whose tangent is 46.2 ÷ 225 or 11° 55′.

The voltage across $r_3 = 10\sqrt{25^2 + 0} = 250.0$ volts.

$$r_1L_1 = 10\sqrt{60^2 + 94.2^2} = 1170.0 \text{ volts.}$$
$$K_1 = 10\sqrt{0 + 147.3^2} = 1473.0 \text{ volts.}$$
$$K_2 = 10\sqrt{0 + 106.2^2} = 1062.0 \text{ volts.}$$
$$r_2L_2 = 10\sqrt{130^2 + 113.1^2} = 1743.0 \text{ volts.}$$
$$r_4 = 10\sqrt{10^2 + 0} = \frac{100.0}{5715.0} \text{ volts.}$$

This shows that the numerical sum of the E. M. F.'s is greater than the impressed E. M. F., though at any instant the vectorial sum of the separate E. M. F.'s is equal to the impressed E. M. F. At a given instant the E. M. F.'s across the capacities is zero, and at that instant the value of the impressed E. M. F. is 2296 cos 11° 55′ = 2250, while that across r_3 is 250 volts, across r_4 is 100 volts, across r_1L_1 is 600 volts and across r_2L_2 is 1300 volts, whose sum is 2250 volts.

Parallel Circuits.

Problems concerning the relation between E. M. F. and current values in alternating current circuits connected in shunt or parallel are best solved by means of formulæ derived from current diagrams.

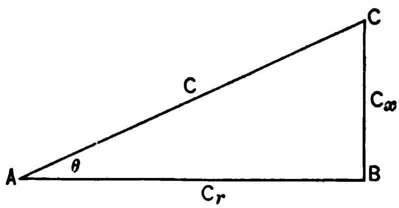


FIG. 115.—Alternating Current Vector Diagram.

The current in any branch can be resolved into two components, one in phase with the E. M. F. and the other in quadrature, or at right angles to it. Such a diagram is shown in Fig. 115. Cr is the component of the current in phase with the E. M. F. and Cx the component in quadrature with it.

From this figure it is seen that

$$C = \sqrt{Cr^2 + Cx^2},$$

$$\cos\theta = \frac{Cr}{C}; \qquad (1)$$

and from a similar vector diagram, involving the quantities resistance, reactance and impedance, represented respectively by AB, BC and AC, and in symbols by r, x and $\sqrt{r^2+x^2}$ or Z.

$$\cos\theta = \frac{r}{Z}, \tag{2}$$

and

$$C\sqrt{r^2+x^2} = E. \tag{3}$$

(1)=(2) or

$$Cr = C\frac{r}{\sqrt{r^2+x^2}}$$

or

$$Cr = \frac{Cr\sqrt{r^2+x^2}}{r^2+x^2};$$

and substituting the value of E from equation (3)

$$Cr = E\frac{r}{r^2+x^2}.$$

Similarly it is shown that

$$Cx = E\frac{x}{r^2+x^2}.$$

Calling $E = 1$, we have

$$Cr = \frac{r}{Z^2}.$$

$$Cx = \frac{x}{Z^2}.$$

$$C = \frac{1}{Z}.$$

These last three terms are given the following names:

$\frac{r}{Z^2}$ = **conductance**, represented by g. (4)

$\frac{x}{Z^2}$ = **susceptance**, represented by b. (5)

$\frac{1}{Z}$ = **admittance**, represented by Y. (6)

And the following relation holds:

$$Y = \sqrt{g^2+b^2}.$$

In pure shunt or parallel circuits, the **total conductance** in circuit is equal to the **arithmetic** sum of the separate conductances; the **total susceptance** is equal to the **algebraic** sum of the separate susceptances, and the **total admittance** is equal to the **geometric** or **vector** sum of the total conductance and the total susceptance.

A pure shunt circuit is shown in Fig. 116, showing a source of E. M. F. G and six shunt circuits, r_1 and r_4 being non-inductive resistances, L_2 and L_5 inductances of resistances r_2 and r_5 respectively, and K_3 and K_6 capacities.

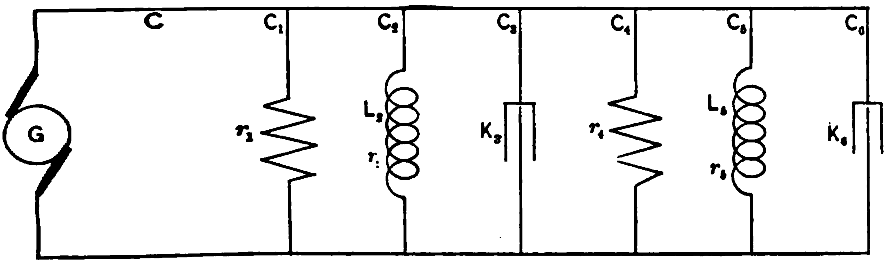


FIG. 116.—Parallel Alternating Current Circuits.

Calling E the E. M. F. of the generator, we have from the foregoing that

$$E = CZ$$

or

$$C = EY.$$

The conductance of the circuits is

$$g_1 = \frac{r_1}{r_1^2 + x_1^2},$$

but x_1, the reactance $= 0$, and

$$g_1 = \frac{1}{r_1},.$$

$$g_2 = \frac{r_2}{r_2^2 + x_2^2},$$

$$g_3 = \frac{r_3}{r_3^2 + x_3^2} = 0, \text{ as } r_3 = 0,$$

$$g_4 = \frac{r_4}{r_4^2 + x_4^2} = \frac{1}{r_4} \text{ as } x_4 = 0,$$

$$g_5 = \frac{r_5}{r_5^2 + x_5^2},$$

$$g_6 = \frac{r_6}{r_6^2 + x_6^2} = 0, \text{ as } r_6 = 0;$$

and the total conductance is

$$G = g_1 + g_2 + g_4 + g_5.$$

The susceptance of the circuits is

$$b_1 = \frac{x_1}{r_1^2 + x_1^2} = 0, \text{ as } x_1 = 0,$$

$$b_2 = \frac{x_2}{r_2^2 + x_2^2},$$

$$b_3 = -\frac{x_3}{r_3^2 + x_3^2} = -\frac{1}{x_3} \text{ as } r_3 = 0,$$

$$b_4 = \frac{x_4}{r_4^2 + x_4^2} = 0, \text{ as } x_4 = 0,$$

$$b_5 = \frac{x_5}{r_5^2 + x_5^2},$$

$$b_6 = -\frac{x_6}{r_6^2 + x_6^2};$$

and the total susceptance is

$$B = b_2 - b_3 + b_5 - b_6.$$

The admittance for any one circuit is

$$y = \sqrt{g^2 + b^2}$$

and the total admittance is

$$Y = \sqrt{G^2 + B^2}$$

and

$$Y = C \text{ when } E = 1.$$

Example.—As an illustration of the foregoing, suppose the factors represented in Fig. 116 have the following values:

$r_1 = 25$ ohms, $r_2 = 60$ ohms, $r_4 = 10$ ohms, $r_5 = 130$ ohms; $L_2 = .25$ henry, $L_5 = .3$ henry, $K_3 = 18$ m. f., $K_6 = 25$ m. f.

It is required to find the current in the mains and in each circuit when 100 volts are impressed on the circuit with a frequency of 60.

For convenience in preparing data for problems of this nature it is well to adopt a form similar to the one following:

Circuits	1	2	3	4	5	6
R	25	60	0	10	130	0
L	0	.25	0	0	.3	0
K	0	0	.000018	0	0	.000025
ωL	0	94.2	0	0	113.1	0
$\frac{1}{\omega K}$	0	0	—147.35	0	0	—106.1
X	0	94.2	—147.35	0	113.1	—106.1
Z	25	111.7	—147.35	10	172.3	—106.1
g	.04	.0048	0	.1	.00438	0
b	0	.00755	—.00678	0	.00381	—.00942
Y	.04	.0089	.00678	.1	.00580	.00942

$$G = g_1 + g_2 + g_4 + g_5 = .1492,$$
$$B = b_2 - b_3 + b_5 - b_6 = -.0048,$$
$$Y = \sqrt{G^2 + B^2} = .1496,$$
$$C = EY = 14.96 \text{ amperes.}$$

As there is the same potential difference across all the circuits

$$E = C_1 Z_1 \text{ or } C_1 = \frac{100}{25} = 4.000,$$
$$= C_2 Z_2 \text{ or } C_2 = \frac{100}{111.7} = .890,$$
$$= C_3 Z_3 \text{ or } C_3 = \frac{100}{147.35} = .678,$$
$$= C_4 Z_4 \text{ or } C_4 = \frac{100}{10} = 10.000,$$
$$= C_5 Z_5 \text{ or } C_5 = \frac{100}{172.3} = .580,$$
$$= C_6 Z_6 \text{ or } C_6 = \frac{100}{106.1} = .942.$$

These values may be also found from the general equation

$$
\begin{aligned}
C &= EY, \text{ thus} \\
C_1 &= EY_1 = 100 \times .04 &&= 4.000, \\
C_2 &= EY_2 = 100 \times .0089 &&= .890, \\
C_3 &= EY_3 = 100 \times .00678 &&= .678, \\
C_4 &= EY_4 = 100 \times .1 &&= 10.000, \\
C_5 &= EY_5 = 100 \times .0058 &&= .580, \\
C_6 &= EY_6 = 100 \times .00942 &&= .942.
\end{aligned}
$$

The phase of the current is given by

$$\theta = \tan^{-1}\frac{B}{G} = -\frac{.0048}{.1492} = -1^\circ\ 50',$$

or the current leads the E. M. F. by an angle of 1° 50′.

Series and Parallel Circuits.

Circuits containing both series and parallel connections may be considered as divided into circuits which contain only pure series or pure parallel connections, and the impedance found for each as

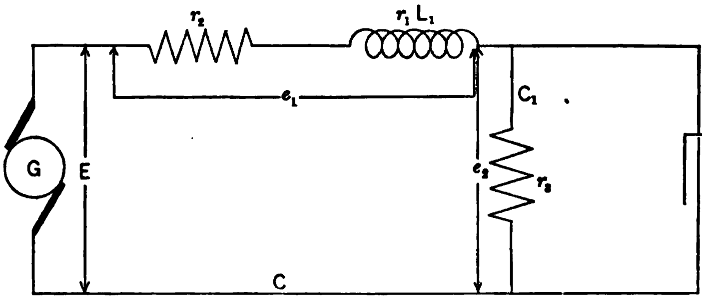


FIG. 117.—Series and Parallel Connections.

described in the two preceding sections. The total impedance is then found by adding them geometrically. Such a circuit is shown in Fig. 117. One is a series circuit and carries the current C, and the other is a shunt circuit with the E. M. F. e_2 impressed on it.

The vector diagram for the series circuit is shown in Fig. 118, as ABC, from which the resulting impedance Z_1 is found. The triangle of admittance for the shunt circuit FGH is drawn with the

conductance g and susceptance $-b$, and the admittance Y is found. In the C_1 circuit there is conductance but no susceptance, and in the C_2 circuit there is susceptance and no conductance. The equivalent impedance of the shunt circuit is the reciprocal of the admittance and Z_{11} is then found from $Z_{11} = 1/Y$. This has the same phase position as Y and CE is drawn parallel to FH, and CE is made equal to Z_{11}. The triangle CDE is then constructed, in which R^1 is the equivalent resistance and X^1 is the equivalent reactance of the parallel circuit. From the separate impedances Z_1 and Z_{11}, the total impedance Z is vectorially found.

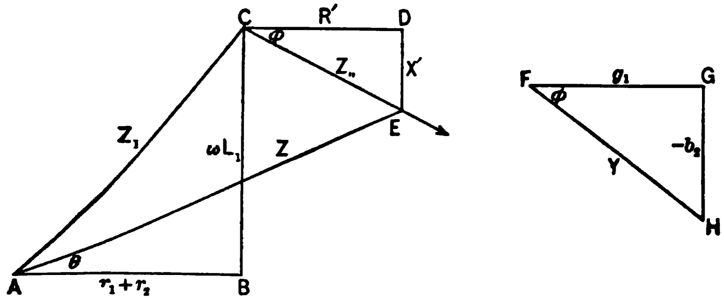


FIG. 118.—Vector Diagram of Series and Parallel Connections.

From an inspection of the preceding figures, the following equations follow:

$$e_1 = CZ_1, \quad e_2 = C_1r_3 = C_2\frac{1}{\omega K},$$

$$C_1 = e_2Y_1 = e_2\sqrt{g_1^2 + b_1^2} = e_2g_1 = \frac{e_2}{r_3},$$

$$C_2 = e_2Y_2 = e_2\sqrt{g_2^2 + b_2^2} = -e_2b_2 = -e_2\omega K,$$

$$E = CZ = C\sqrt{(r_1 + r_2 + R^1)^2 + (\omega L_1 - X^1)^2},$$

$$\tan\phi = \frac{b_2}{g_2}, \quad R^1 = Z_{11}\cos\phi, \quad X^1 = Z_{11}\sin\phi.$$

Parallel circuits containing series connections are shown in Fig. 119. The circuit can be divided into three series circuits connected in parallel. The admittance of each circuit may be found and all

added together geometrically to obtain the total admittance, from which the E. M. F. or current can be found.

The vector diagram is shown in Fig. 120.

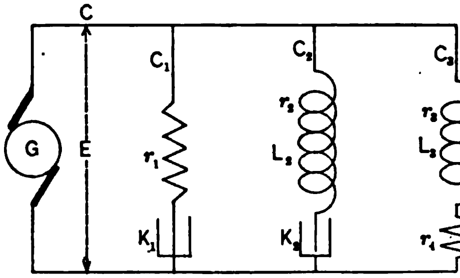


FIG. 119.—Parallel Series Connections.

b_2 may be $+$ or $-$, depending on the values of L_2 and K_2, but is shown as $-$. In these diagrams directions to the right are considered $+$, to left $-$, up is $+$ and down is $-$, starting from an

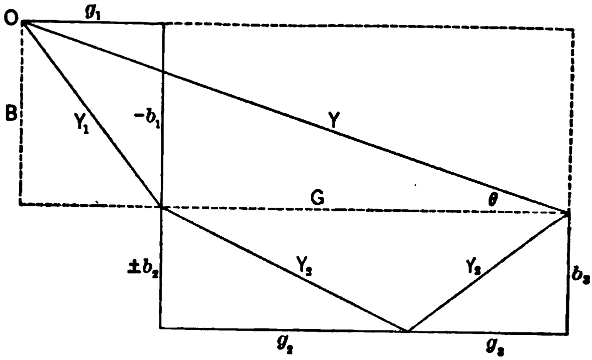


FIG. 120.—Vector Diagram of Fig. 119.

origin O. The admittances for the three branches are marked $Y_1 Y_2 Y_3$ and the total admittance is marked Y and is equal to $\sqrt{G^2 + B^2}$. The phase angle is θ, an angle of lead, caused by the preponderance of condensive reactance and is equal to

$$\theta = \tan^{-1} \frac{B}{G}.$$

An inspection of Figs. 119 and 120 will show the following equations hold:

$$C_1 = EY_1 = E\sqrt{g_1^2 + b_1^2},$$
$$C_2 = EY_2 = E\sqrt{g_2^2 + b_2^2},$$
$$C_3 = EY_3 = E\sqrt{g_3^2 + b_3^2},$$
$$C = EY = E\sqrt{G^2 + B_2}$$
$$= E\sqrt{(g_1 + g_2 + g_3)^2 + (-b_1 - b_2 + b_3)^2}.$$

In general

$$g = \frac{r}{r^2 + x^2},$$

where r is resistance and x is reactance, and

$$b = \qquad ,$$

$$g_1 = \frac{r_1}{r_1^2 + \left(\frac{1}{\omega K_1}\right)^2},$$

$$b_1 = \frac{\frac{1}{\omega K_1}}{r_1^2 + \left(\frac{1}{\omega K_1}\right)^2},$$

$$g_2 = \frac{r_2}{r_2^2 + (\omega L_2)^2},$$

$$b_2 = \frac{(\omega L_2)^2}{r_2^2 + (\omega L_2)^2},$$

$$g_3 = \frac{r_3 + r_4}{(r_3 + r_4)^2 + (\omega L_3)^2},$$

$$b_3 = \frac{(\omega L_3)^2}{(r_3 + r_4)^2 + (\omega L_3)^2}.$$

E. M. F. Triangles of Parallel Circuits.—The preceding method uses the vector diagram of admittances, but the same result may be obtained in parallel circuits by constructing a vector diagram of E. M. F.'s, involving resistances and reactances, in place of conductances and susceptances.

In Fig. 121 EA is drawn to scale to represent the value of the impressed E. M. F., or, if unknown, to a convenient scale, and the three triangles EBA, ECA and EDA are the triangles of the three E. M. F.'s. $R_1R_2R_3$ are the resistances in the circuits EB, EC and

ED respectively, and C_1, C_2 and C_3 are the currents in those branches, or $C_1R_1 = EB$, $C_2R_2 = EC$ and $C_3R_3 = ED$.

Suppose in the circuit represented by EAB, there is a net inductive reactance equal to ωL_1, in that represented by EAC, there is a net capacity reactance equal to $1/\omega K_2$, and in that represented by EAD there is a net inductive reactance of ωL_3. These values will be represented respectively by AB, AC and AD. They all might have capacity or inductive reactance or both.

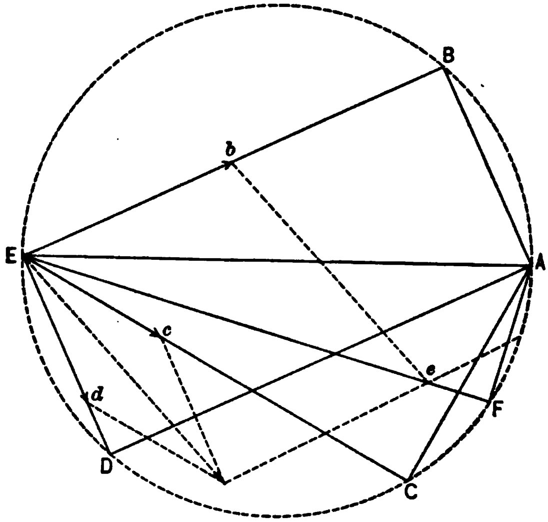


FIG. 121.—E. M. F. Vector Diagram of 3 Parallel Circuits.

Dividing EB by R_1, EC by R_2 and ED by R_3, the separate current values in each circuit are obtained, which are represented by $Eb = C_1$, $Ec = C_2$ and $Ed = C_3$. The total current is obtained by taking the vector sum of C_1, C_2 and C_3 which is illustrated by the dotted lines and represented by Ee. This is the current that would flow if a single conductor of equivalent resistance and impedance was substituted for the parallel branches.

In the triangle EFA, EF represents the total current $\times$ the *equivalent resistance*, AF, the total current $\times$ the *equivalent reactance*, and EA, the impressed E. M. F., or the total current $\times$ the *equivalent impedance*.

Solutions of problems involving divided circuits may be solved either graphically by laying off the known values according to scale or mathematically, and the phase angles may be measured by means of a protractor or found mathematically.

Example.

As an example of the two methods given for the solution of divided circuit problems, the following problem is solved by each of the methods:

Problem.—An alternating current of 25 amperes, with a frequency of 150, flows in a circuit in one place by parallel branches; one of 4 ohms resistance and .003 henry inductance, the other of 12 ohms resistance and 200 microfarads capacity. Determine the impressed E. M. F., the equivalent impedance of the parallel branches, the resistance and reactance of the equivalent circuit, and the current values of the separate circuits.

First Method.—

Circuits.		1	2	
R		4	12	ohms
L		.003	0	henries
K		0	.0002	farads
ωL		2.83	0	
$\frac{1}{\omega K}$		0	5.3	
Z		4.9	13.1	
Z^2		24	172.1	
g		.166	.07	
b		.118	—.031	
Y		.2036	.0765	
G	.2036		.0871	
B	.0871			
G^2	.0556			
B^2	.0076			
Total Y	.2514			
Total Z	3.97			

$$C = EY,$$

$$E = \frac{25}{.2514} = 99.4 \text{ volts,}$$

$$C_1 = EY_1 = 99.4 \times .2036 = 20.24 \text{ amperes,}$$

$$C_2 = EY_2 = 99.4 \times .0765 = 7.6 \text{ amperes.}$$

The total admittance is

$$Y = .2514,$$

and the total impedance $= \frac{1}{Y} = \frac{1}{.2514} = 3.97$ ohms.

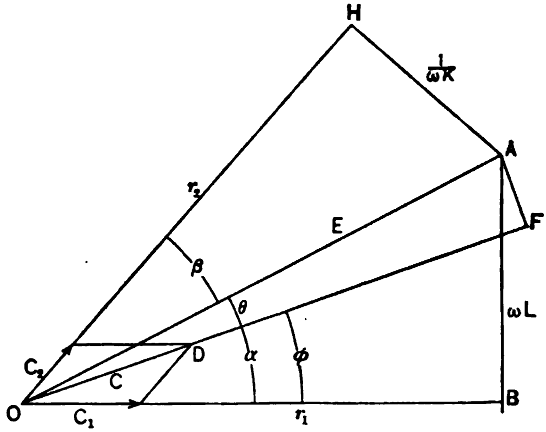


FIG. 122.—Vector Diagram of E. M. F.'s, Two Parallel Circuits.

The total or equivalent resistance is

$$R = G \times Z^2 = .236 \times (3.97)^2 = 3.715.$$

The total or equivalent reactance is

$$X = B \times Z^2 = .0871 \times (3.97)^2 = 1.373.$$

Second Method.—Referring to Fig. 122 and to the preceding section.

$$E = C_1 Z_1 = C_2 Z_2$$

or

$$\frac{C_1}{C_2} = \frac{13.1}{4.9} = 2.67,$$

$$C_1 = \frac{OB}{r_1} = \frac{OB}{4},$$

$$C_2 = \frac{OH}{r_2} = \frac{OH}{12},$$

$$C^2 = C_1^2 + C_2^2 + 2C_1C_2\cos(\alpha + \beta),$$

$$\tan\alpha = \frac{\omega L}{r_1} = .705, \quad \alpha = 35^\circ\ 10',$$

$$\tan\beta = \frac{\frac{1}{\omega K}}{r_2} = .442, \quad \beta = 23^\circ\ 50',$$

$$(2.67C_2)^2 + C_2^2 + 5.34C_2^2\cos 59^\circ = 625,$$

$$C_2 = 7.58 \text{ amperes},$$

$$C_1 = 2.67 \times 7.58 = 20.24 \text{ amperes},$$

$$E = C_1 \times 4.9 = 99.2 \text{ volts}.$$

The equivalent resistance is $OF \div C$.
The equivalent reactance is $AF \div C$.
The equivalent impedance is $OA \div C$.

$$OF = OA\cos\theta, \quad AF = OA\sin\theta,$$

$$\frac{C_2}{C} = \frac{\sin\phi}{\sin 121^\circ} \text{ or } \phi = 15^\circ\ 05',$$

$$\theta = \alpha - \phi = 20^\circ\ 05',$$

$$AF = 99.2\sin 20^\circ\ 05' = 34.07,$$

$$OF = 99.2\cos 20^\circ\ 05' = 93.19.$$

The equivalent resistance $= \frac{93.19}{25} = 3.73$ ohms.

The equivalent reactance $= \frac{34.07}{25} = 1.36$ ohms.

The equivalent impedance $= \frac{99.2}{25} = 3.97$ ohms.

Resonance.

In a constant potential circuit in which there is inductive reactance and condensive reactance connected in series, a high rise in

E. M. F. may be obtained by regulating the reactances or the frequency. The expression for E, the total impressed E. M. F., is

$$E = C\sqrt{R^2 + \left(\omega L - \frac{1}{\omega K}\right)^2}.$$

The E. M. F. across the condenser terminals is

$$e = C\frac{1}{\omega K}$$

or

$$\frac{e}{E} = \frac{\frac{1}{\omega K}}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega K}\right)^2}}.$$

If the denominator of the second member of this equation, the impedance, be less than unity, e will be greater than E, and if $\omega L = \frac{1}{\omega K}$ and R is 0,

$$\frac{e}{E} = \infty.$$

This is an extreme case of resonance and could only occur in such an ideal case, but in any case, e/E will be a maximum when $\omega L = \frac{1}{\omega K}$. When this latter condition exists, the frequency is

$$n = \frac{1}{2\pi\sqrt{KL}}.$$

A circuit with a certain self-induction, capacity and resistance tends to oscillate electrically at a certain frequency. If such a circuit be placed in a medium in which electric waves of the frequency of its own circuit, given by the expression $n = \frac{1}{2\pi\sqrt{KL}}$ are passing, each wave will give a slight impulse to the readily excited circuit, which will gradually grow in intensity. This phenomenon is known as **resonance**, and finds its greatest use in wireless telegraphy, where alternating circuits of low frequency are changed to oscillating currents of extremely high frequencies, the number per second being given from the above expression when K is expressed in farads and L in henries.

Transformers.

The elementary principle of the transformer was briefly explained in Chap. VIII. In its most simple form it is a device for changing the voltage in an alternating current system from one value to another, with an inverse change in the value of the current. In its simple mechanical details it consists of two independent coils wound on an iron or other permeable core, with the windings closely interlaced and insulated from each other. The coil in which is impressed the available voltage is called the *primary* and the other the *secondary* voltage.

The alternating voltage impressed on the primary coils produces a current, and this current produces a magnetomotive force, dependent upon the number of turns in the coil, which causes a magnetic flux in the core. As the current is an alternating one, the flux will alternate from zero to a maximum and to zero, with the phenomenon repeated in the opposite sense. Assuming a sine wave for the impressed E. M. F., the rate of change of the magnetic flux must be greatest when the E. M. F. is greatest, and is zero when the E. M. F. is zero. The flux is thus 90° behind the impressed E. M. F. This changing flux, caused by the impressed E. M. F., cuts the various turns of both primary and secondary windings and induces an E. M. F. in each of them.

One *CGS* unit of E. M. F. is induced in each turn when the flux changes at the rate of one line per second. Calling this E. M. F., e and the flux N,

$$e = \frac{dN}{dt}.$$

When the flux varies according to the sine function with t, the value of $N = AB_{max} \sin \omega t$, where A is the area of cross section of the core, and B_{max} is the maximum value of the flux in lines per unit or area; ω is the electrical velocity, equal to $2\pi n$, where n is the frequency, or number of cycles per second.

$$e = \frac{dN}{dt} = \frac{d(AB_{max} \sin \omega t)}{dt}$$

or

$$e = AB_{max}\, \omega \cos \omega t.$$

The maximum value of the cosine is unity, and the maximum value of e is

$$e_{max} = AB_{max}\,\omega.$$

The virtual value of e is $e \div \sqrt{2}$, and therefore E is in volts

$$e = \frac{AB_{max}\,2\pi nS}{\sqrt{2} \times 10^8} = \frac{4.45AB_{max}\,nS}{10^8}$$

The above expression is the fundamental equation of the transformer, and is the E. M. F. induced in each of the two windings, as determined by the values of S, the number of turns in each coil. The E. M. F. induced in the windings of the primary is 90° behind the flux, and as this, as already shown, is 90° behind the impressed E. M. F., it acts as a counter E. M. F. The E. M. F. induced in the secondary windings is also given by the fundamental equation and it is this E. M. F. which gives rise to current in the secondary.

With the secondary on open circuit, the only current in the primary is that necessary to produce the flux indicated in the fundamental equation. This current is very small and under this condition the primary acts as a choke coil with small resistance and large impedance, and the counter E. M. F. is very nearly equal to the impressed E. M. F.

The current required to produce this flux is called the *exciting* current and is composed of two components, one called the *magnetizing* and the other the *hysteretic* component. The latter is necessary to overcome the internal friction in turning the molecular magnets first in one direction and then in the other, and is a direct loss, being dissipated in heat. This loss requires the hysteretic component to be in phase with the impressed E. M. F., while the magnetizing component is in quadrature with it.

As stated above, when the secondary is on open circuit there is generated in each of its turns an E. M. F. equal to the counter E. M. F. per turn in the primary, with a total E. M. F. as given by the fundamental equation. If, now, the secondary circuit is closed through a resistance, this E. M. F. gives rise to a secondary current, which is, in general, in phase with the E. M. F., and is opposed in phase to the primary current. The secondary ampere turns will be opposed to the primary ampere turns, and there will be a tendency

to demagnetize the core and to reduce the flux. As this is reduced, the counter E. M. F. of the primary is reduced and the primary current increased to such a value that its ampere turns will restore the flux to its former value, the additional current being just sufficient to overcome the demagnetizing effect of the secondary current.

The counter E. M. F. in the primary regulates itself according to variations of load on the secondary in a manner similar to the counter E. M. F. of a motor under varying loads. "A continuous current motor runs at such a speed as to generate an E. M. F. which is less than the value of the impressed E. M. F. by an amount which is just sufficient to force through the armature a current of such a value that its product with the field magnetism gives the torque demanded at the shaft." Similarly in a transformer, "the magnetomotive force due to the ampere turns of the primary current (the secondary being open) causes lines of force to be produced in the core, and the change in the value of these lines with the alternation of the current generates in the primary coil, an E. M. F. in time phase position to tend to decrease the current in the coil; the final result being that there flows in the coil just that value of current whose product with the number of primary turns gives the magnetomotive force necessary to send through the reluctance of their path that number of lines, the change in value of which generates in the primary coil an E. M. F. less than the impressed by an amount just sufficient to allow this current to flow through the local impedance of the primary coil." * After the secondary circuit is closed, "stable conditions will be reached when the additional primary current has a value and phase position such as to give the magnetomotive force necessary to counterbalance the effect of the secondary ampere turns, thus keeping the flux in the core nearly at the constant value demanded by the primary E. M. F." *

Ratio of Voltages and Currents.—As more current is drawn from the secondary more flows in the primary and the transformer is almost perfectly automatic in its performance. The losses amount to only a few per cent of its capacity and practically all the power supplied to the primary is delivered to the secondary. The power

* Alternating Current Motors, McAllister.

supplied is the terminal voltage times the primary current, and the output is the terminal voltage times the secondary current, or

$$C_1E_1 = C_2E_2$$

or

$$\frac{C_1}{C_2} = \frac{E_2}{E_1}.$$

The current necessary to magnetize the transformer is very small on account of the closed magnetic current and the permeable material, and the number of ampere turns in the primary is practically equal to the opposing secondary ampere turns, or

$$N_1C_1 = N_2C_2,$$

but the E. M. F.'s are proportional to the number of turns in each coil, so

$$N_1E_2 = N_2E,$$

and as before

$$\frac{C_1}{C_2} = \frac{E_2}{E}.$$

The above relations only hold in an ideal transformer, one without resistance or reactance. Whenever there is resistance there must be potential drop, and if the supply voltage is maintained constant, the secondary terminal voltage will fall on increase of load.

Efficiency.

The efficiency of a transformer is expressed by the ratio of the net output to the gross imput, or by the ratio of the output to the output plus all the losses.

Losses.—Losses in a transformer, as in any induction machine, are of two kinds, core and copper losses. The core losses comprise eddy current losses and hysteresis loss. Eddy currents vary as the square of the current and hysteresis loss directly as the current. Eddy currents are eliminated to a great extent by making the core of laminated iron, with the laminations parallel with the magnetic flux.

Hysteresis loss is due to the power required to turn the molecular magnets first in one direction and then another and depends directly on the frequency of the alternations.

Copper losses are due to the currents flowing through the coils. In an unloaded secondary, this loss is very small, as both the value of the exciting current and resistance are small quantities. When regularly loaded, the copper loss in watts is equal to $C_1{}^2r_1 + C_2{}^2r_2$. The expression for the efficiency then becomes

$$\text{eff.} = \frac{E_2C_2}{E_2C_2 + \text{eddy losses} + \text{hysteresis losses} + \text{copper losses}}.$$

The copper losses increase with the load, and with the magnetic leakage (the flux which interlaces with one coil and not the other) cause a drop of potential in both the primary and secondary windings.

Transformer Vector Diagram.

The vector diagram shows graphically and illustrates the terms used to describe the action of a transformer. It is shown in Fig. 123, the transformation ratio being assumed unity.

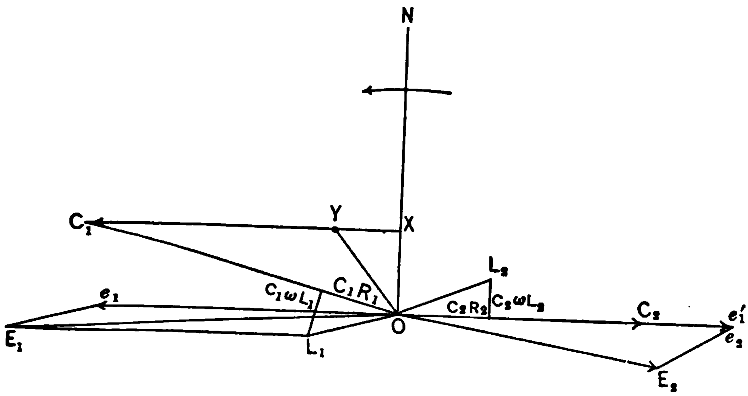


FIG. 123.—Vector Diagram of Transformer.

ON is drawn to represent the vector of the useful flux, common to both windings, and is produced by the exciting current *OY*, which has the two components, *OX* and *XY*, the former the magnetizing component which produces the flux, and the latter the hysteretic component which is lost as heat and which requires added current for its compensation.

The alternating flux ON induces the E. M. F.'s, Oe_2 and $Oe_1{}^1$ in the secondary and primary windings and they are represented by vectors perpendicular to the flux vector, as the phase is 90° difference. The secondary E. M. F., Oe_2, produces current C_2, which causes a drop in its windings due to its resistance and magnetic leakage. The resistance drop is represented by C_2R_2 in line with the current and reactance $C_2\omega_2L_2$ perpendicular to it. The resultant drop is OL_2, which added vectorially to Oe_2 gives OE_2, the terminal voltage of the secondary windings.

C_2 produces a demagnetizing action which requires YC_1 amperes in the primary to overcome it. This, combined with the exciting current OY, gives a total primary current equal to OC_1. This primary current causes a drop of C_1R_1, which is drawn in line with OC_1, and an inductance drop of $C_1\omega L_1$, which is drawn at right angles to it. The resultant drop is OL_1.

$Oe_1{}^1$ or Oe_1 represents the counter E. M. F. of the primary, as it is 90° behind the flux, which in turn is 90° behind the impressed E. M. F., and the impressed E. M. F. must have a value equal to the resultant of the counter E. M. F. of the primary and the resultant drop in the primary. OE_1, the impressed E. M. F., is the vector sum of Oe_1 and OL_1.

The phase angle is shown by θ, the angle C_1OE_1, the angle between the vector lines representing the current and impressed E. M. F., and it is an angle of lag.

Problems on Alternating Currents.

1. With a frequency of 100, what is the impedance of a circuit of 5 ohms resistance, .2 henry inductance and 1 microfarad capacity? What is the phase relation of the current and E. M. F.?

2. What current will flow in a circuit of 10 ohms resistance, .02 henry inductance and 200 microfarads capacity, if 1000 volts at a frequency of 120 are impressed on its terminals?

3. An E. M. F. of 1000 volts, with a frequency of 100, is impressed upon a circuit of 5 ohms resistance, 10 microfarads capacity, and .1 henry inductance, all in series. What is the voltage across the terminals of the condenser, and between the extremities of the inductance?

4. An alternating current supply develops a maximum value of 50 volts in a circuit of 4 ohms resistance, the frequency of the alternations

being 60, and the value of the resistance E. M. F. 40 volts. Find the self-induction of the circuit and the angle of lag or lead. Suppose the angle of phase was 0°, what would be the value of the resistance E. M. F.?

5. An alternating circuit has a frequency of 60 and an inductance of 1 henry. What would be the value of the capacity that would neutralize it?

6. What is the value of the applied E. M. F. required to maintain a current of 20 amperes in a circuit having no inductance, but a resistance of 4 ohms and a capacity of 400 microfarads, frequency being 60?

7. An alternating wattmeter reads 500, voltmeter 100 and ammeter 10, what is the phase angle?

8. If the inductance of a meter for measuring the length of electromagnetic waves is 12 microhenries, what will be its capacity when measuring a wave length of 1000 meters, velocity of light being 300 million meters per second?

9. A coil of wire has an inductance of .025 henry and a resistance of 25 ohms and is connected in an alternating current circuit. With a frequency of 60, what maximum E. M. F. is required to maintain 25 amperes in it? When the value of the inductance E. M. F. is half its maximum value, what is the value of the ohmic E. M. F.?

10. An E. M. F. of 10,000 volts, with a frequency of 50, is impressed upon a circuit of 4 parallel branches; one of 100 ohms resistance and 2 henries inductance, one of 400 ohms and 5 microfarads capacity, one of 300 ohms and 3 henries inductance and one of 600 ohms, 4 henries inductance and 1 microfarad capacity. Find the current that will flow in each branch and the equivalent resistance, reactance and impedance.

11. A step-up transformer has 100 turns in the primary and a transformation ratio of 1 to 10. Assuming 100 volts to be impressed on the primary, what is the secondary terminal E. M. F. and the number of secondary turns?

12. A system consists of a generator, a step-up transformer having 200 primary and 3000 secondary turns, a transmission line and a step-down transformer having 3750 primary and 50 secondary turns. The step-down transformer is to supply current at 400 volts. What must be the E. M. F. of the generator, neglecting all losses?

13. In the preceding problem suppose there is 1% loss in each transformer and 5% loss in the line. How much must the generator voltage be increased to keep the secondary voltage constant at 400 volts?

CHAPTER XVI.

DYNAMO ELECTRIC MACHINES.

A dynamo electric machine is defined to be one for converting energy in the form of mechanical power into energy in the form of electric currents or vice versa by magneto-electric induction, the operation being in general that of setting conductors to rotate in a magnetic field.

So far the dynamo electric machines considered have been the generator and the motor, one furnishing and the other absorbing continuous currents. Besides these machines considered as simple units, there are others built from combinations of these two, with combinations of alternating and continuous E. M. F. and currents, each designed to satisfy some definite requirement.

Motor Generators.

These machines are generally designed to change from a continuous current at one voltage to a continuous current at another voltage, and are sometimes called **continuous current transformers.** To do this it is necessary to employ a rotating apparatus which is a combination of a motor and a generator. Two complete machines may be used, each with its own armature and own commutator, fixed to a common shaft, or one single armature may be wound with two separate windings connected to separate commutators. In the first case, there would be two separate magnetic fields and in the second there would be but one.

Current is supplied to one set of windings through its proper commutator at a certain voltage, and the field being excited this machine will act as a motor and will drive the other set of windings as a generator, generating an E. M. F. at its brushes, whose value depends upon the number of windings, the speed and the strength of the field.

If the speed and field are the same, the E. M. F. developed in

each winding is proportional to the number of turns of wire in the winding.

Using the notation of Chapter XII, the relation between the various E. M. F's. and currents are given in the equations:

For motor,

$$\mathfrak{E} = E_1 + C_{1a} r_{1a} . \tag{1}$$

For generator,

$$e = E_2 - C_{2a} r_{2a} . \tag{2}$$

The ratio of E_1 to E_2, the *total* E. M. F's. generated by each winding is constant, or

$$\frac{E_1}{E_2} = k,$$

and so will also the ratio C_1 to C_2 be constant, as

$$E_1 C_{1a} = E_2 C_{2a} \text{ or } \frac{C_{2a}}{C_{1a}} = k,$$

or from (1)

$$E_1 = \mathfrak{E} - C_{1a} r_a = \mathfrak{E} - \frac{C_{2a} r_{1a}}{k}, \tag{3}$$

and from (2)

$$E_1 = ek + C_{2a} r_a k, \tag{4}$$

and from (3) and (4)

$$e = \frac{\mathfrak{E}}{k} - \left(\frac{r_{1a}}{k^2} + r_{2a} \right) C_{2a} .$$

This gives an expression by which e, the difference of potential at the generator brushes can be found from $\mathfrak{E}$, the difference of potential at the motor brushes.

The amount of power developed by the generator depends on the efficiency of the system, which is the ratio of the input of the motor to the output of the generator, or using the previous notation

$$\text{Efficiency} = \frac{eC_2}{\mathfrak{E} C_1}$$

where C_1 represents the current absorbed by the motor and C_2 the current delivered by the generator. Thus a system with an efficiency of 80 per cent, absorbing 50 amperes at 125 volts would deliver the 50 amperes at 100 volts, thus

$$\frac{125 \times 50 \times 80}{100 \times 100} = 50,$$

or if the windings in the generator were only half as many it would deliver 100 amperes at 50 volts.

Motor generators are required for purposes involving the supply of current of a nature and voltage different from that of the ship's distribution system. As far as practicable they must conform to the requirements and specifications given for all motors, Chap. IV, Vol. II.

Among the purposes for which they are used are the following:

Purpose.	*Generator Capacity.*	*Current Supply.*
Interior communication.	2 kilowatts.	25 volts direct current, adjustable to 20 volts.
Turret danger-zone signal, or gun-firing and sight-lighting.	1½ kilowatts.	125 volts alternating current, single phase, 60 cycles.
Gyro compass.	1 ampere per phase.	125 volts alternating current, 3 phase, 60 cycles.
Telephone talking.	Torpedo boat, 50 watts; battleship, 500 watts.	20 volts direct current, adjustable to 15 volts.
Telephone ringing.	25 watts dynamotor.	75-85 volts alternating current, single phase, 16⅔-20 cycles.
Warning signals.	As specified.	As required for pole changes for operating howlers.

Rotary Compensators.

These are machines built very much like motor generators and are used to change the voltage of one continuous current to other voltages of continuous current. Their particular action is more fully described under descriptions of various turret-turning systems. They consist in general of two complete machines with separate armature windings, commutators and brushes, and with separate magnetic fields. The armatures are mounted on a common shaft. In their first operation they are motors, but deliver currents to other motors at varying voltages by changing the excitation of their fields.

Extracts from specifications issued by the Navy Department follow:

"The compensator to be entirely enclosed and water-tight, but provided with openings of sufficient size and number to give easy access to the commutator, brush rigging and field coils, such openings to be provided with water-tight covers and clamping devices of approved construction.

"The field frame will be of steel and enclose two separate magnetic circuits; it will be separable in a horizontal plane through

the axis to permit of ready removal of armature and field coils. The two armatures will be carried on one shaft of ample strength, and forced ventilation or fans on the armature shaft will not be permitted. The compensator to be capable of wall or ceiling suspension.

"Fields will be so compounded as to best adapt the machine to the purpose for which it is intended. The series winding is to compensate for the resistance drop in the armature and leads to the motors, and shall be such as to give as nearly a straight line compounding curve as possible.

"The set to be designed for operation at 120 volts across the line. The maximum speed of the compensator must not exceed 1500 R. P. M."

A description of a rotary compensator as actually installed is given by the makers, the General Electric Company.

Rotary Compensator.

The rotary compensators are totally enclosed and consist of a common cast-steel magnet frame, containing two field magnetic circuits and enclosing two armatures mounted upon one shaft supported in bearing heads at the outside ends.

Magnet Frame.—The magnet frame consists of a cast-steel shell octagonal in shape and separable in a horizontal plane through the armature shaft. Steel bolts hold the halves of the frame together and feet are cast with the lower half for fastening the motor-generator set to its support.

Openings are made at the top, sides and ends of the frame to give access to the brushes. The covers for these openings are all solid sheet metal made water-tight by rubber gaskets. The covers over the commutator and at the frame ends will be secured by wing bolts, thus making them easily removable for inspection and adjustment of the brushes.

Pole Pieces.—Four laminated steel pole pieces in each frame support and retain the field coils and are held in position by bolts passing through the magnet frame.

Armature Bearings and Linings.—The armature bearings of the self-oiling and self-aligning type, are cast with the end shields

which fit accurately bored seats in the ends of the magnet frame. Oil rings supply ample lubrication, and a combination sight and overflow gauge is provided with each bearing of such a height that oil will not overflow inside the magnet frame. Holes in the top of the bearings, furnished with suitable covers, provide means for filling the oil wells and inspecting the oil rings and provision is made for drawing the oil from the reservoirs.

The split linings are of bronze and held from turning by dowel pins.

Field Coils.—The field coils fit around and are held in place by the pole pieces. They are insulated with pressboard and varnished cambric and then treated with several coats of insulating baking japan, making them thoroughly water-proof. The ends of the windings are soldered to connectors. The fields of both machines are compound wound, the shunt being over the series.

Armatures.—The armatures are of the multiple drum type having laminated steel cores, with air ducts for ventilation, supported on cast-steel spiders separately keyed to the shaft with commutators at the ends. The cores are slotted to receive the armature coils, the slots being punched in the laminations before being assembled. The coils are form wound, thoroughly insulated with oiled muslin, tape and japan, and securely held in the slots of the armature core by binding wires.

Commutators.—The commutators consist of hard drawn copper segments carefully insulated with mica and supported on cast-steel shells which are securely keyed to the shaft. The ends of the armature coils are soldered into the commutator segments.

Brush Rigging.—The brushes of carbon and of ample cross-section are carried in brush holders supported on four insulated brass studs bolted to an adjustable yoke. The brush holders are supplied with adjustable springs for regulating the brush tension and alternate studs are connected by bus rings.

Series Field Shunt.—The adjustable shunt on the series field consists of a slate having two terminals about 10 inches apart, upon which German silver strips can be bolted, the adjustment to suit ship conditions, being obtained by changing the number or section of these strips.

Cables and Connections.—The frame is to be supplied undrilled so that it can be tapped for conduit by purchaser for armature and field leads to suit ship conditions.

External Field.—There will be no appreciable field at a distance of 15 feet from the machine in any direction.

Non-Corrosive Parts.—All small screws, nuts, etc., which are liable to become corroded and thus broken in removal are to be made of non-corrosive metal and not of iron or steel. Flat springs are to be of phosphor bronze, and spiral springs of steel, copper-plated.

Tests.—The compensator will be subjected to the following tests:

(1) With the two shunt fields connected in parallel across the line, the armatures being in series, the set is to be run without load for a continuous period of three hours. At the end of this time the temperature rise of the shunt fields must not exceed 50° C. measured by resistance.

(2) The set to be immediately started and run under conditions of full current and maximum voltage in the large motor (corresponding to minimum current in the field of armature for operating small motor) for a continuous period of one hour.

(3) Within one-half hour after completion of test (2) the set is to be run for a period of one hour under conditions of minimum compensator voltage and full current to large motor.

The temperature rise under the above conditions shall not exceed the following:

Series field	70° C.	by thermometer.
Shunt field	50° C.	by resistance.
Commutator	65° C.	by thermometer.
Armature	60° C.	by "
Bearings	35° C.	by "
Other parts	60° C.	by "

In addition, the compensator is to be subjected to an overload of 50 per cent for five minutes under the conditions specified in (2) and (3) above.

All windings are to withstand 1500 volts alternating for one minute.

Weight.—The approximate weight of the set is 3000 pounds.

Dynamotors.

These are machines for supplying continuous currents at various voltages. They differ from motor generators in the fact that they have but one field for both the motor and generator while the motor generator has a separate field for each. This makes a much better balanced arrangement than the two fields of the motor generator, as all armature reactions are neutralized; there is no tendency to spark at the brushes and the brushes do not have to be shifted for changes of load, as all reactions due to generator characteristics are balanced by those of the motor which act in a contrary sense. Any change in the field affects both motor and generator, and will simply make them run faster or slower.

The armature coils are wound on the same core, and in general the coils of the motor are wound first and imbedded in slots. Those for the generator wound over them are connected to a commutator at the opposite end from the motor connections.

Dynamotors are used on shipboard for reducing the voltage of the main generators to lower values for use with the different systems of interior communication.

They are ½ horsepower and take about 3 amperes at 125 volts, transforming to 20 volts for general alarm bells and by adding auxiliary brushes, 13.3 and 6.6 volts may be obtained for call bell or other work.

Rotary Converters.

These machines are constructed for changing a continuous current into an alternating current, or vice versa. Like motor generators, they may be built with separate armatures and commutators with separate fields or with but one armature with one winding and one field, fitted with two commutators, one for continuous current and one for the alternating current.

In those built as two separate machines with the armatures secured to one shaft, the action is simply that one may be used as a continuous-current motor to deliver alternating currents at the other commutator, or alternating currents may be supplied to drive one, delivering continuous current at the other commutator.

The case of one armature with one winding with connections to a

commutator and collector rings, one connection for continuous current and for alternating currents, requires some explanation.

Let Fig. 124 represent a single ring armature revolving between a pair of magnetic poles, two opposite points being connected with collecting rings, C and C, upon which brushes make contact to take off the current.

When the armature is in the position shown, all the wires on each half are sending current in the same direction, and let the winding and field be such that it is up in both halves, making the outer ring C positive and the inner one negative.

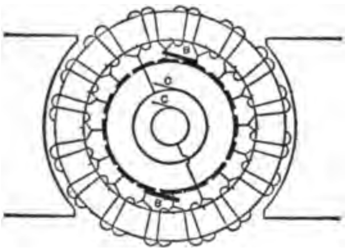


FIG. 124.—Diagram of Rotary Converter.

Now suppose the armature has turned a quarter turn, then, as before, all the wires on each side are trying to send current towards the top, but the connections to the rings have turned with the armature and there is no connection at the top to take it off. The E. M. F's. generated on the two sides of each half are opposed and exactly equal, so there is no net E. M. F. between the collecting rings and there is no current at that instant. Between the positions when the connections are vertical and horizontal the E. M. F. and current vary more or less uniformly.

Now suppose the armature is provided with a commutator, each section of the armature connected to a commutator bar, and with brushes B and B, which make contact with the commutator segments. These brushes make contact with different segments of the commutator as the armature revolves, while C and C always make contact with but one section of the armature winding.

It is seen then that the armature wires between B and B all

tend to send current in the same direction at all positions of the armature, so that a continuous current may be taken from *B* and *B*, while at the same time an alternating current may be taken from the same armature by *C* and *C*.

Since either a continuous or an alternating current may be obtained from the same armature, it makes no difference what causes the armature to rotate, and therefore if continuous current be applied to the brushes *B* and *B* alternating current may be taken from the brushes *C* and *C*; and similarly, if alternating current be supplied to the brushes *C* and *C* the machine will run as an alternating current motor and continuous current taken from *B* and *B*.

Relation of Voltages between the Continuous Current and Alternating Current Brushes.—From Fig. 124 it is seen that the alternating voltage is at a maximum when the armature coils connected with the collecting rings are also connected with the continuous current brushes, and therefore the maximum value of the alternating voltage is equal to the steady value of the continuous voltage. The **mean** value of the alternating voltage is only 70.7 per cent of the maximum, while the actual values vary from zero to the maximum.

Different Phase Currents.—A rotary converter with only two collecting rings as shown, would give a single-phase current. Two-phase currents could be obtained by having a second pair of collecting rings connected to the armature windings at points midway between the first ones. The E. M. F. between one pair would be a maximum when that between the other pair was at zero. The currents would then be at right angles and the effective values of the E. M. F's. would be equal. By connecting three collecting rings to three equidistant points a **three-phase** current could be obtained from a rotary.

In the three-phase current, the effective voltage between any two of the collecting brushes is 62 per cent of the continuous voltage.

Rotary Converters for Wireless Sets.

These machines are of the two-field, two-armature type, with one end fitted with a commutator for continuous currents and the other

with collector rings for alternating current. The armature is driven as a motor by continuous current from the ship's power mains, driving the other as alternator.

The object to be gained is simply the conversion of continuous current into alternating current for use in the primary of induction coils used in wireless sending apparatus, without much change in potential. It is usual to insert variable resistances in the field of each armature so as to vary the voltages of each within small limits.

Size of Converters.—Converters are rated according to their output capacity expressed in kilowatts. Thus a 5-kilowatt converter is one whose product of E. M. F. at the terminals and output current is equal to 5000 watts or 5 kilowatts. Thus one form used has an input of 125 volts with 52.5 amperes and an output of 110 volts and 45.5 amperes, or practically 5 kilowatts.

CHAPTER XVII.

TESTS AND EXPERIMENTS WITH DYNAMO ELECTRIC MACHINES.

The general idea of making tests of a completed machine is to discover whether it complies with the specifications under which it was constructed and is able to supply a certain amount of power. At the same time, it is by actually experimenting with electrical machines that a sound knowledge of their underlying principles may be most readily gained.

General Tests.

As a matter of procedure in making tests of dynamo electric machines the following list gives a general indication of the points to be considered:

1. The general study of the machine.
2. Mechanical strength of parts against breaking.
3. Balance of armature.
4. Sparking at the brushes.
5. Noise.
6. Resistances of the various windings; armature, field, etc.
7. Characteristic curves for internal, external and total circuits.
8. Variation of speed under different loads and temperatures.
9. Dielectric strength and insulation resistance.
10. Heating.
11. Efficiency.
12. Determination of losses.
13. Determination of E. M. F. around armature.

Study of a Dynamo.

Under this head the following general points should be particularly considered:

1. Tabulation of electrical and mechanical points of design.
2. Adjustment and fit of parts.
3. Lubrication.
4. Workmanship and material.

A careful inspection of the machine should be made while at rest, noting every point connected with the field, armature, commutator, brushes, brush rigging, headboard, etc., so that facts ascertained can be compared with the specifications, or if none are furnished, the points developed will help to make a complete description of the machine.

The general form of the field frame should be noted with the number of field spools and poles, also the method used to connect the terminals of the windings from one field spool to another. The number of the terminals on each spool will indicate the form of field winding; whether series, shunt or compound. If a compound machine it will be seen whether the two windings are separate or one on the other, noting which is on the outside. An inspection will show whether the pole pieces and magnet core are in one with the field frame or whether they are separate and bolted together.

The construction of the armature would show its type of winding, whether ring or drum, and the fact should be noted whether the conductors are wound directly on the armature core or are imbedded in slots. The commutator segments should be counted and the method of securing the armature windings to them noted; that is, whether they are clamped, screwed or soldered.

The kind and number of brushes should be noted and the mechanical design of the brush holders and the means employed to move all the brushes together should be examined. The brushes should be removed and replaced to become familiar with the various springs and attachments and the brushes should be rocked back and forth by the rocker arm and clamped in different positions.

The headboard should be inspected and the different terminals marked, so that the series and shunt terminals and armature and equalizer leads can be readily distinguished. This will also show whether the machine is a long shunt or short shunt in case it proves to be a compound machine.

The maker's name-plate furnishes important information, such as the power expressed in kilowatts, the revolutions of the armature per minute to produce the required E. M. F., the E. M. F. at the terminals, the current output, type of field winding, etc. This information should be tabulated to be verified by tests and experiments.

Adjustment and Fit of Parts.—The adjustment and fit of all parts should be carefully examined and particular attention should be given to the brush rigging. Brush holders ought to be readily accessible for adjustment and renewal of brushes and springs, and adjustable for tension, generally without tools, and constructed to admit of proper staggering of brushes.

Lubrication.—All bearings should be provided with oil wells of sufficient capacity and inspection should be made to see if any arrangement is provided to prevent oil running along the armature shaft. The best practice requires self-oiling bearings provided with split babbitted bearing linings, and visual oil gauges for determining the amount of oil in pockets and drains for drawing off oil.

Workmanship and Material.—Naturally the materials and workmanship of all parts of any machine should be of the best quality, and notes should be made of any particular part that shows evidence of inferior workmanship or defective or cheap material, and all windings should be carefully observed for any signs of abrasion of the insulation or outside covering. Special attention should be given to the workmanship and material of the brush rigging and springs. The best practice requires all metal portions to be non-corrosive and fitted with flexible connections between brush and holder. Brushes should be carefully examined and their quality should be such as to give perfect contact without cutting, scratching or smearing the commutator.

Mechanical Strength.

All the main parts of dynamo electric machines as the base, field frames, field magnets, armature, shaft, bearings, etc., should be of such strength that they will not spring with any reasonable force. The strength to resist centrifugal forces due to the armature revo-

lution should be tested by running the armatures to at least double their normal speed without load, and series motors should be run at four times their full-load speed. There should be no signs of weakening of any part of the armature when run at these increased speeds for at least thirty minutes.

Balance of Armature.

Before commencing any test requiring the movement of the armature, carefully turn it by hand or jack over the engine if directly connected to its shaft, looking at the same time for any obstruction to free movement. When satisfied that all is clear make ready for slowly turning over the armature with the motive power supplied.

In case of a steam engine, either directly driven or by means of a belt, see the oil service in working order, and take all the usual precautions in starting the engine; exhaust open, water clear of cylinders, drains and relief valves open, bearings oiled and that the cylinders have been properly warmed. In turning over the armature for the first time make sure that the external circuit is opened and that the brushes are raised clear of the commutator.

Open the throttle and let the engine turn slowly and watch the revolution of the armature, noting whether it revolves concentrically; that it does not strike the pole pieces at any point; that there is equal clearance between armature and the pole pieces all around and that it runs smoothly and free from undue vibration. The alignment of the shaft should be noticed and one not true would soon manifest itself by heated bearings and these must be watched from the time the engine is started.

The perfection of balance of armatures of generators should be tested by running them at least 25 per cent above their normal speed; of shunt motors at their normal speeds; of series motors from normal to double their rated speeds, and of compound motors from normal speed to 50 per cent above normal. In all cases the armatures of well-designed machines should not show the slightest vibration.

Sparking at the Brushes.

The causes of brush sparking are given in Chapter XXII and if any sparking occurs during a test, its cause should be sought and the machine credited with a defect. Modern well-designed generators and motors should show no signs of sparking whatsoever under any changes of load within their capacity and generators under ordinary conditions should show no sparking when overloaded 25 per cent, nor should any change in the brushes be a necessity to prevent it.

Motors to run in the open should show no signs of sparking from no load to full load and enclosed motors from no load to 25 per cent overload and without shifting the brushes. No sparking should also hold under all conditions of weak or strong field.

Noise.

All armatures of generators and motors should run at their full rated speed and load practically without noise or humming sounds and without rattling or chattering of the brushes.

Resistance of Windings.

The ohmic resistances of all parts of the armature windings, series and shunt windings should be carefully measured and recorded so that the values of the fall of potential through the various circuits can be checked and the calculated value of the external energy compared with that actually obtained.

A method for measuring these resistances is given in the chapter on Measurements. All the different methods used for measuring such small resistances as that of a large armature or the series winding are based on the "fall of potential" method and require the use of some standard small resistance, and the accuracy of the measurement depends on that of the standard resistance. The method described in the chapter referred to is available for use on board ship with the instruments usually furnished, but if a laboratory is available other methods can be used with possibly more accuracy; and such is one given below.

Measurement of Armature Resistance by Comparison of Deflections.—This depends on the following general principle: *If two resistances have the same current flowing in them, the differences of potential at their ends is proportional to their resistances.*

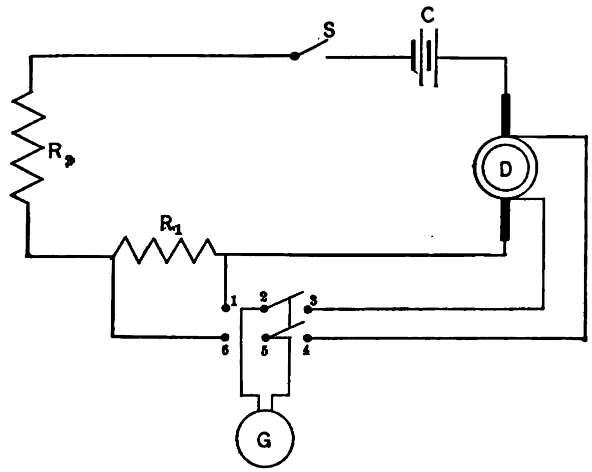


FIG. 125.—Measurement of Armature Resistance.

In Fig. 125

D is the armature and resistance,
R_1 standard resistance, approximately equal to that of D,
R_2 variable resistance,
C one or two cells (preferably secondary cells),
G galvanometer,
S switch,
1, 2, 3, 4, 5, 6 terminals of a double-pole, two-throw switch.

The leads of the circuit containing the cells are connected to the brushes, disconnecting the field windings. The wires from the armature to the galvanometer are connected between the brushes and the commutator, making sure that the wires press on opposite segments and make contact with one segment only.

The galvanometer should have a uniformly divided scale and its reading should be proportional to the deflecting current. If it is a

very sensitive one, it may be necessary to use a shunt, or a resistance in series with it will often give the desired result.

The resistances of the leading wires to the galvanometer does not affect the accuracy of the measurement as they are so very small compared with that of the galvanometer, and the latter may be far removed from the machine where it will be free from any influences other than the deflecting current.

Instructions for Test.—Close the switch S and by means of the switch hinged at 2 and 5 connect the galvanometer to 1 and 6, so that it is connected to the circuit containing the standard resistance. Adjust resistance R_2 to get a good readable deflection. Note the deflection on the scale of the galvanometer. Reverse the switch to 3 and 4, connecting to armature and note the deflection. Reverse the switch and repeat the first reading, and repeat the whole operation five or six times.

Let d_1 be the mean of all the deflections when connected to R_1,
d_2 be the mean of all the deflections when connected to D,
V_1 the fall of potential through R_1,
V_2 the fall of potential through D.

Then

$$\frac{d_1}{d_2} = \frac{V_1}{V_2},$$

and by the principle stated above

$$\frac{V_1}{V_2} = \frac{R_1}{D},$$

or

$$\frac{R_1}{D} = \frac{d_1}{d_2} \text{ and } D = \frac{R_1 d_2}{d_1}.$$

Connecting the leading wires from the galvanometer to the brushes will give the resistance of armature, brushes and contacts, and subtracting this value from the armature resistance will give the resistance of brushes, brush holders and contacts; an item sometimes of great importance.

This method is suitable for measuring resistances between .1 and .001 ohm, but for resistance lower than these values, other methods must be resorted to, such as that by the Thompson bridge, which will measure as low as .0001 ohm.

Measurement of the Resistance of Field Windings—Series Winding.—As this is of very low resistance, either the method given in the chapter on Measurements or the method given above may be used, inserting the series winding directly in series with the cell circuit.

Shunt Winding.—Either of the two methods given in the chapter referred to may be used, viz., by the Testing Set or Bridge, or by the Voltmeter and Ammeter method.

In measuring the resistance of the shunt winding, it is usual to measure both the *cold* and *hot* resistance. The voltage applied to the shunt terminals should be the normal working voltage and readings of the voltmeter and ammeter should be taken at regular intervals of time.

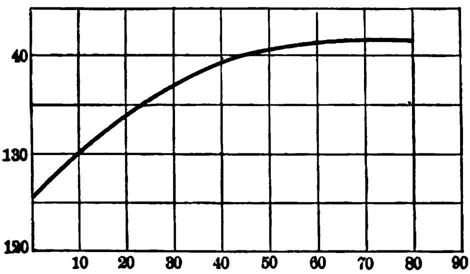


FIG. 126.—Curve of Resistance.

Curves plotted with intervals of time as abscissæ and the resistances obtained at the corresponding time as ordinates are instructive. Fig. 126 shows a curve obtained in this manner.

The numbers on the bottom line represent minutes of time and those on the left, resistance in ohms. This shows that the resistance at first increased rapidly with the time, then more slowly and became approximately constant after an hour's time of running, and the greatest value would be the *hot* resistance.

Characteristic Curves.

Characteristic curves of electrical machines have been referred to in the chapter on Generators, but it is the purpose here to go more into the details of the methods used in obtaining these curves and

to show graphically the necessary connections for making this part of the electrical tests.

The following curves are the most important ones for which data are taken for tests or experiments on generators of the classes named: **Series generator:** *external circuit; total circuit; magnetization.* **Shunt generator:** *external circuit; internal circuit; total circuit; armature.* **Compound generator:** *compound; differential series, external circuit; internal circuit.*

Characteristics of a Series Generator.—The curve usually obtained by observation is the external circuit curve as this can be found by connecting up a voltmeter to show the fall of potential in the external circuit, and by including an ammeter in the circuit. The connections are shown in Fig. 127.

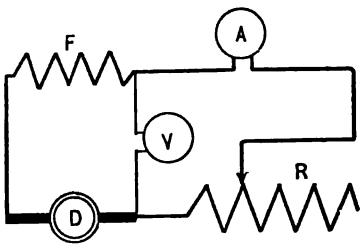


FIG. 127.—Connections for External Circuit Characteristic of Series Generator.

The voltmeter V is connected to the terminals of the machine (note, not to the brushes) and the ammeter A is included in the main circuit in which there is a variable resistance R.

Instructions.—Add resistance in R until both the E. M. F. and current are quite small, and take simultaneous readings of both instruments and record them. Then vary (decrease) R by successive amounts so that successive points on the curve can be obtained, it being generally advisable to make the reading an even number of amperes for convenience in plotting. This operation can be carried on up to the safe carrying capacity of the machine.

For any given value of current a small change of speed produces an approximately proportional change of E. M. F., so if the speed varies, which should be tested at each reading by a tachometer, the

voltmeter readings should be corrected to some convenient constant speed near the mean.

With the data obtained plot the amperes as abscissæ and the differences of potential as ordinates, according to some convenient scale, and draw a fair curve through the points obtained.

Then with the resistances of the armature and field, calculate the volts lost in the armature and field for each value of C, by the equation $C(r_a + r_m)$, see Chaper XII, and plot the internal resistance line. Then add these values vertically to each of the points on the curve corresponding to the values of C, which will give a series of points, through which the **total circuit curve** can be drawn. These curves are shown in Fig. 77.

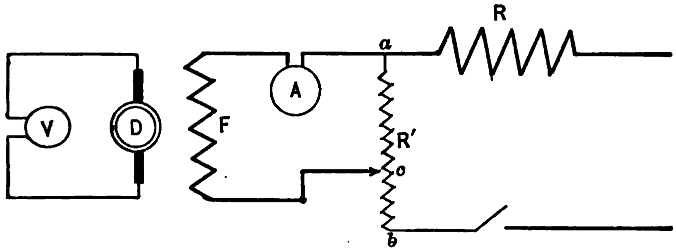


FIG. 128.—Connections for Obtaining Magnetization Curve.

Magnetization Curve.—This curve shows the relation between the exciting field current and the resulting E. M. F. produced by the armature at no load.

The diagram of connections is shown in Fig. 128.

The series field F is disconnected and the voltmeter V is connected to the brushes of the armature D. The field winding is connected to an outside source of E. M. F. of value equal to that produced by D. The change of exciting current may be effected in either of two ways and both are given for purposes of instruction. R, a variable resistance may be changed, thereby effecting change of current in F, or the difference of potential at the terminals of F may be varied by the resistance R'. This is a resistance of sufficient carrying capacity not to become overheated when permanently connected to the source of supply and also carrying the field current. The field winding is connected to one end of this

resistance, *a,* and to a movable point *c,* which slides along *ab.* As *c* is moved towards *a,* the difference of potential between *a* and *c* decreases, consequently decreasing the current through *F.*

Instructions.—Begin with the exciting current zero or very small, by varying either *R* or *R'* or both. Note the simultaneous readings of *A* and *V.* Vary the exciting current as desired and note the readings, and continue this until the maximum current in *F* is reached. Then decrease the current by similar steps. For each value of *A* read *V,* and note the speed of *D.* Reduce the readings of *V* to some constant speed from the formula

$$V=\frac{V'n}{n'}$$

where V' and n' are the E. M. F. and observed speed and V the desired E. M. F. and n the normal speed.

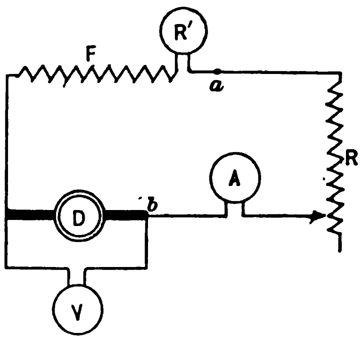


FIG. 129.—Connections for Obtaining Shunt Internal Characteristic.

With the observed values, plot curves as before, with current as abscissæ and E. M. F. as ordinates for both ascending and descending values of exciting current. It will be found that this gives two distinct curves, and the failure of the two curves to coincide is due to the *hysteresis* of the magnetic circuit, and the distance apart of the curves will be an indication of the nature of the metal used in the circuit as regards hysteresis. Soft iron shows little hysteresis while hard iron or steel shows the effect very strongly.

The form of the magnetization curve resembles very closely that of the total circuit curve of the series machine, which should be natural, as the E. M. F. is directly proportional to the magnetization and that in turn to the amperes of the exciting current.

Characteristics of a Shunt Generator—Internal Characteristics. —The curve of the internal circuit is obtained by disconnecting the external circuit; that is by leaving it open, when the machine

practically becomes a series machine with the external circuit short-circuited, so the resulting curve should show the general form of the series total or magnetization curves.

The connections to be made for obtaining the necessary data are shown in Fig. 129.

The terminal *a* of the shunt field *F* with its regulator is disconnected from *b* and between these points is inserted the variable resistance *R* with ammeter *A* in circuit. This resistance is added to allow a greater change of voltage and resulting current so as to obtain more points on the curve.

Instructions.—It is well to start this experiment with very little magnetization, or with all resistance in the regulator and *R*. When the armature is running at its normal speed, and all resistance in, take readings of *A* and *V*. Then vary the resistances till the ammeter shows an even number of amperes as 5 or 10, and read *V*, checking the speed at the same time. Then make *A* read 10, then note *V* and so on up to the safe carrying capacity of *F* or to the point of saturation of the magnets. Correct all speeds to that of the mean speed as previously explained.

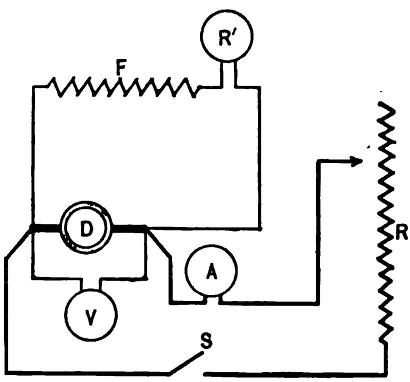


FIG. 130.—Connections for Obtaining Shunt External Characteristic.

With the data obtained, the curve can be plotted in the usual way with amperes as abscissæ and volts as ordinates. If the experiment was commenced with low resistance or high magnetization and the current stepped down, the resulting curve would be slightly different from the first and as the curves are all for the purpose of comparison, it is better to take them starting from the same point; that is, with either increasing or decreasing magnetization.

External Shunt Characteristic.—The connections for obtaining the necessary data for this curve are shown in Fig. 130.

There are no changes in the connections of the machine itself,

but the variable resistance *R* is introduced in the external circuit with the ammeter in circuit.

Instructions.—At first leave the outside circuit open and adjust the regulator in the field so that the generator at normal speed will give the normal E. M. F. This gives the first point on the curve, zero current and maximum E. M. F. Do not change the regulator resistance during this experiment.

Close the external circuit through switch *S* with enough resistance in *R* to give a small resulting current in external circuit. This is a matter of simple calculation, knowing the E. M. F. and the current desired, the amount of resistance is readily known.

Read both *A* and *V* and note speed. Vary *R* for a new value of *A* and note the simultaneous readings and take the revolutions to be corrected as in other cases already described.

It is more than probable that starting as above, the safe-carrying current will be reached before the curve can be completed; that is, before the E. M. F. falls sufficiently to cause its resulting current to drop. In this case start with a lower E. M. F. on open circuit by changing the regulator and then the complete curve may be obtained.

The general form of these curves is shown in curve 1 (Fig. 80) and also the method of obtaining the other curves from this one.

Precautions.—To obtain good results, care should be taken not to break the circuit or to make too large changes in the variable resistance.

If at any time a new point is further from the last one taken than desired, it is better not to go back, for the curves for increasing and decreasing magnetization are different.

If the external circuit should be broken while working on the lower part of the curve, the magnetization would run up at once and if the circuit was now closed through the same resistance, there would be danger of getting an excessive current before the magnetization would fall to its previous state. In this case it would be better to throw all resistance in before closing the switch and then gradually reduce it till the conditions are the same as before the break.

When the resistance is nearly all out so that the E. M. F. has

fallen, bringing the lower end of the curve near the current line, the curve for increasing magnetization may then be started without any break of circuit or change of any kind, and if care is exercised and the change of resistance is very small and gradual, the two curves can be completed, forming a loop at the lower end.

If the up curve is to be started first, the field circuit should be left open before closing the external circuit, or short-circuiting the brushes (all the external resistance being out). After the external circuit is closed the field circuit can be closed, for then the E. M. F. at the brushes and current in the field is almost zero. The value of current for zero potential at the brushes depends upon the

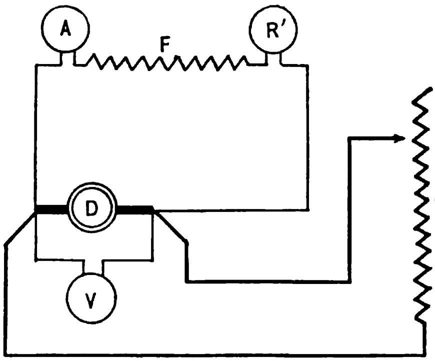


FIG. 131.—Connections for Obtaining Armature Characteristic.

resistance of the armature and the E. M. F. due to residual magnetism. If the field excitation is gradually reduced from a high value to zero, the E. M. F. due to residual magnetism will have a higher value than when the circuit is suddenly broken.

The increase in resistance of the field coils due to increase in temperature affects the resulting curve as does also self-induction and armature reactions and as every effect has its cause, much may be learned by the experimenter in taking these curves.

Armature Characteristic.—This is a curve that shows the relation between the external current and the field current when the difference of potential at the terminals is kept constant and is useful in studying the compounding of a generator, the departure of

the curve from a straight line showing the change in the field current to be compensated for by series turns on the shunt machine.

The connections for making the test are shown in Fig. 131.

An ammeter is connected in the field circuit and the usual variable resistance R in the external circuit.

Instructions.—Adjust the E. M. F. at the brushes with the external circuit open to the value at which the difference of potential is to be kept constant. Then close the external circuit through the maximum resistance used, adjust the field regulator so as to give the same E. M. F. as before and then read A and V. Change

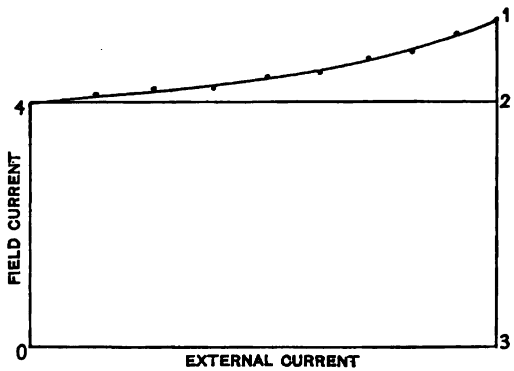


FIG. 132.—Armature Characteristic.

the resistance R slowly, adjust the E. M. F. to its constant value, and read A and V. The curve will have the general form shown in Fig. 132.

The distance 1, 2 on the scale of field current shows the field current that must be added by series turns to produce an E. M. F. of the external current 03 equal to the original E. M. F. producing field current 04.

Characteristics of a Compound Generator.—The compound machine, being merely a shunt generator with the addition of a series field of a few turns, may be used as a shunt generator by leaving out the series coils. The connections are then made and the *external* and *internal* characteristics are then obtained as previously described under the shunt generator.

To obtain the series characteristic the shunt field is disconnected and the procedure is the same as given under the Series Generator.

Compound Characteristic.—The connections for obtaining the data for plotting the compound characteristic curve is shown in Fig. 133.

This shows a "long shunt" machine with the voltmeter V connected across both armature D and series field F' and the ammeter in the external circuit.

Instructions.—Before closing the external circuit adjust the E. M. F. to the same value as that for the external shunt characteristic, so the two curves will start from the same point on the

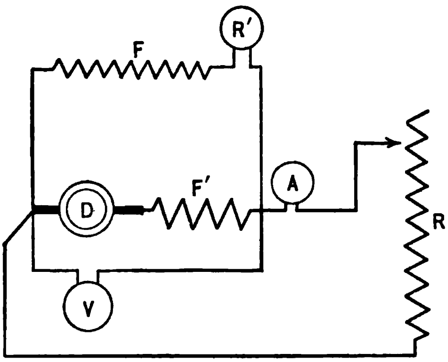


FIG. 133.—Connections for Obtaining Compound Characteristic.

ordinate axis. When the field regulator is once adjusted to give the proper voltage do not change it during the experiment.

Close the external circuit through a resistance that will give a small current and take simultaneous readings of A and V, and at same time take the speed to reduce the voltage to the normal speed. Proceed by small changes in the resistance R and obtain values for A and V.

By disconnecting the series coils and connecting them so that the current through them is reversed, the **differential curve** is obtained. As the field is weakened by increase of current in the series coils, which oppose the shunt, the curve drops more rapidly than the external shunt and the maximum current is much smaller.

Curves showing the relative differences between the characteristics of a compound generator are shown in Fig. 134.

Variation of Speed.

The allowable variation of armature speed of dynamo electric machines under different conditions of load and temperature depends on the kind of work for which they are designed. Modern well-designed machines should show very close regulation of speed,

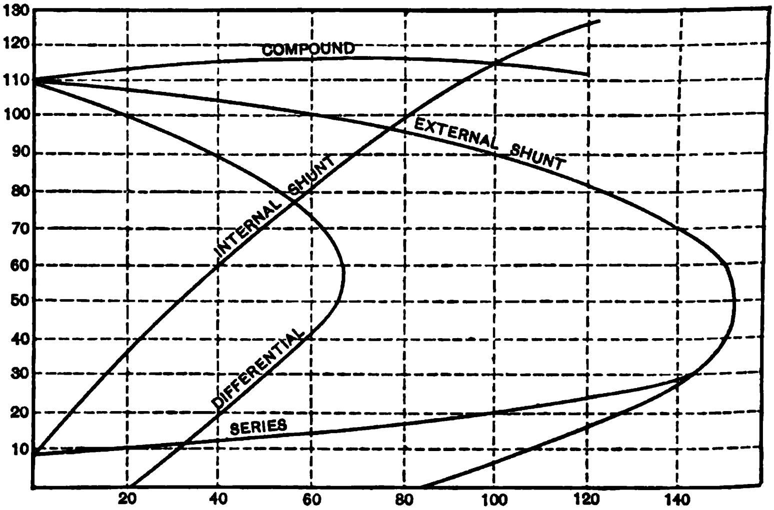


FIG. 134.—Characteristic Curves of a Compound Generator.

and as illustrating the amount of variation considered to be practical, the specifications for machines used on ships of the navy are quoted.

For main generators the speed variation must not exceed 2½ per cent when load is varied between full load to 20 per cent of full load, gradually or in one step, engine running with normal steam pressure and vacuum. A variation of not more than 3½ per cent is allowed when full load is suddenly thrown on or off the generator, with constant steam pressure, either normal or 20 per cent above normal. A variation of not more than 3½ per cent is

allowed when 90 per cent of full load is suddenly thrown on or off the generator, with constant steam pressure at 20 per cent below normal; exhaust in both cases to be either into condenser or atmosphere.

For shunt-wound motors, the variation in speed from no load to full load is not allowed to be more than 12 per cent in motors of less than 5 horsepower and not more than 9 per cent in motors of 5 horsepower and above. Series and compound-wound motors must make their rated outputs at their rated speeds. The motor must be designed to obtain its rated speed when hot, with atmospheric temperature of approximately 25° C. and the speed actually obtained at the end of a heat run must be within 4 per cent of the rated. The variation in speed due to heating should not exceed 10 per cent.

For motor generators of a speed of about 2000 revolutions per minute, such as used for gun-elevating equipment, the speed variation between no load and full load and from full load to no load should not exceed 10 per cent of normal. For those of about 1500 revolutions per minute, used in turret-turning equipment, the variation between no load and full load and from full load to no load should not exceed 6 per cent of normal.

For motors for driving machine tools, the variation in speed from no load (hot) to full load (hot) shall not be more than 9 per cent in motors of less than 5 horsepower and not more than 7 per cent in motors of 5 horsepower and over. For all motors the variation from their rated speeds at full load (hot) must not exceed 5 per cent and the variation in speed due to heating must not exceed 10 per cent. For variable speed motors these conditions must be met at any set speed throughout the range.

Dielectric Strength and Insulation Resistance.

There are two distinct properties which the insulation of a completed machine should possess: first, its ability to withstand the application of a high voltage for a long time without deterioration, its *dielectric strength;* second, its ability to offer a sufficiently high resistance to prevent any appreciable leakage in working, its *insulation resistance.*

The insulation of a generator or motor should first be tested by the application of an alternating E. M. F. 5 to 10 times the working pressure of the machine, applied between one of the main terminals and the frame. This will make sure that all conductors are insulated from the iron parts of the machine. Naval specifications for generators and motors require the test for dielectric strength to be made at the end of a heat test with pressures of at least 1500 alternating volts to be applied for a continuous period of one minute, the source of power to be either a generator or transformer of at least 5 kilowatts capacity.

Several methods of measuring insulation resistance are given in the chapter on Measurements and also in the chapter on Care of Electric Plant and Accessories, but specifications for modern machines require a testing voltage of at least four or five times the difference of potential ordinarily to be withstood. The insulation between all parts should be at least one megohm.

Heating.

The heat produced in the conductors of electric machines, in the armature and field windings, commutator segments, in the iron frame work, the field frame, spools and pole pieces, bearings, etc., is energy lost and consequently it is the aim to reduce these losses to a minimum. Different rises of temperature are allowed in different classes of machines, depending on their construction and their location, the general limits being between about 30° C. to 60° C. after four hours' continuous running at full load. The rise in temperature in enclosed motors is allowed to be about 10° C. greater than in open motors.

For generators used in the navy the maximum allowable rise in degrees C. is armature $33\frac{1}{3}$°, commutator 40°, field coils $33\frac{1}{3}$° above a standard room temperature of 25° C.

Rise of Temperature.—It is usual to measure the rise of temperature in the armature and field coils by means of the change of their resistances due to the heat produced and in the commutator and other parts by means of a thermometer.

By Thermometer.—In using the thermometer great care should be used to see that the bulb is well protected by waste or some such

covering to prevent radiation and that the highest temperature is taken. It is obviously impossible to measure the temperature of coils by a thermometer with any degree of accuracy whatever, as the inner layers, which experiment always shows are the hottest, cannot be reached by ordinary thermometers. Difficulty would also be found in getting the hottest part of outside layers as some parts would be cooled by the moving armature more than others.

The thermometer should have a long thin bulb and be placed flat against the surface with as much bearing surface as possible, and well covered with some non-conducting material and if possible should be read in this position.

By Change of Resistance.—To measure the rise in temperature of armature or field conductors, their resistances are measured, as already given, both when hot and cold; that is, the resistances are measured when the machine is at rest and again after four or five hours' continuous run at full load and before they have had time to cool.

Method of Calculation.—The method of calculation in general use and required by navy specifications is that based upon the report of the Committee on Standardization of the American Institute of Electrical Engineers and is as follows:

1. In computing the temperature rise of a coil by change of resistance, the following method should be used:

(a) The total rise in temperature of a coil during a test to be determined by the formula adopted by the American Institute of Electrical Engineers, viz.:

$$\theta = (238 + t)\left(\frac{R_{(t+\theta)}}{R_t} - 1\right)$$

where θ = total rise of degrees Centigrade,
t = cold temperature of the coil,
R_t = cold resistance of coil,
$R_{(t+\theta)}$ = hot resistance of coil,
also let T = final room temperature;

and by the use of this formula it is assumed that .0042 is the temperature coefficient of copper from and at 0° C.

(b) From the total temperature rise calculated as above, subtract the difference between the cold-coil temperature t and the

final room temperature *T*, which should be carefully taken as directed below.

(c) The rise thus obtained above final room temperature to be corrected by one-half of 1 per cent for each degree Centigrade that the final room temperature differs from 25° C. The correction to be added if the room temperature is below 25° C., and subtracted if above it.

In the case, however, of shunt-wound coils subjected to a constant potential, the current strength and therefore the temperature rise will be changed by a change of room temperature. A correction for this should be made by correcting the rise, as above calculated, in proportion as the final absolute temperature of the room differs from the absolute temperature at 25° C. In most cases this correction nearly neutralizes the correction under (c); both corrections are, however, recommended by the American Institute.

2. In connection with the above method, the following instructions should be carefully observed:

(a) The temperature *t* should be taken by a thermometer placed directly on the coil, at the time the cold resistance is taken, and has nothing to do with the cold-room temperature. In taking this cold-coil temperature care should be taken that the coil has not been recently brought from a much colder or hotter place than that in which the test is being made.

(b) The room temperature *T*, above which the temperature rise of the machine is calculated, must be very carefully determined. The temperature of the room should be read from a thermometer placed in such a position that it fairly represents the temperature of the air surrounding the machine. If the room temperature remains constant during the run there will be no question as to the final room temperature; if the temperature varies, however, as is usually the case, for a short run of two hours or less, the average of the entire run should be taken; for a run of six hours or more the average of the last three hours should be taken. Conditions should be such that the room temperature will not vary greatly during the tests, and a variation in room temperature of over 10° C. during a heat run of six hours, or a proportionate change for runs of shorter duration, should in no case be exceeded. If, however, the

temperature is very irregular throughout the run, or changes rapidly at the end, the test should be made over, especially if the machine is near the heating limits of the specifications.

(c) To prevent the sudden fluctuation of room temperature due to the opening of doors, etc., it is recommended that the bulb of the thermometer registering the room temperature be inserted in a hole drilled in a small iron block, the hole to be filled with cylinder oil or mercury. This block can be conveniently made of about the following dimensions: Three inches in length, 2 inches in diameter, with a ½-inch hole, drilled 1½ inches in depth. Care should be taken that the machine under test is not exposed to drafts of air.

3. An example of the above follows:

Length of heat run = 6 hours. The last seven half-hour readings of room temperature are, 19.5, 20, 20.5, 21, 21.5, 22, and 22.5; average, 21° C. = T.

The cold resistance of coils = 150 ohms = R_t.

The hot resistance of coils = 180 ohms = $R_{(t+\theta)}$.

The cold temperature of the coils is 15° C.

Then $\theta = (238 + 15)\left(\frac{180}{150} - 1\right) = 50.6°$ = rise above cold-coil temperature.

The variation from cold-coil temperature to final room temperature is 6 degrees. Then 50.6° — 6° = 44.6° rise above room temperature. The difference between final room temperature and 25° C. is 25° — 21° = 4°. Therefore, 4 times ½ per cent equals 2 per cent correction, or 44.6 × 1.02 = 45.49° rise above room temperature corrected to 25° C.

If the coils were shunt-wound constant-potential coils, the rise should be again corrected in the ratio of 238 + 21° and 238 + 25°, or a rise of 44.79°.

4. In computing temperature rises from thermometer measurements, the rise should be figured above final room temperature T taken as explained in paragraph 2 (b) above, and corrected as directed in paragraph 1 (c) above.

Efficiency.

The question of efficiency of generators has been treated in the chapter on Efficiencies and Losses of Generators and of motors in the chapter on Motors. The efficiency of generating sets should be as high as practicable consistent with good design and the specific requirements, but where thorough reliability and freedom from danger of breaking down are the first requisites, as in motors for turning turrets, elevating guns, hoisting ammunition, hoisting boats, etc., maximum efficiency is often sacrificed to reliability.

The commercial efficiencies required for the main generators installed on ships of the navy are given in the following table:

K. W.	Loads. 1⅓. *Per Cent.*	1. *Per Cent.*	¾. *Per Cent.*	½. *Per Cent.*
2.5	78	78	76	73
5	80	80	78	75
8	83	83	81	77
16	87	87	86	84
24	88	88	87	85
32	88	88	87	85
50	89	89	88	86
100	90	90	89	87

Commercial Efficiency of Generators.—The commercial efficiency is determined by finding the ratio between the power utilized in the external circuit and the total power supplied to the engine of the generator, both expressed in the same units.

The methods used for determining the efficiency are of two kinds:

(1) Methods in which the driving power and the electrical output are both separately measured. These are called *direct* methods.

(2) Methods in which the losses in the generator are determined by electrical measurements. These losses added to the output gives the power supplied to it. These are called *indirect* methods.

Direct Method.—For any given load the power utilized in the external circuit is found by inserting an ammeter in the circuit and connecting a voltmeter to the terminals of the machine. Indicator cards are taken from all cylinders at the same time and the revolutions of the engine are taken.

From the indicator cards, the mean effective steam pressure is

found, and with the area of piston, length of stroke and number of revolutions, the indicated horsepower is found from the formula

$$\text{H. P.} = \frac{2\,plan}{33{,}000}, \tag{1}$$

where $p =$ mean effective pressure in pounds per square inch,
$l =$ length of stroke in feet,
$a =$ area of piston in square inches,
$n =$ number of revolutions per minute.

Dividing the product of the volts and amperes of the external circuit by 746 expresses the external energy utilized in horsepower, thus

$$\text{H. P.} = \frac{eC}{746} \tag{2}$$

and the commercial efficiency $= \frac{(2)}{(1)}$.

Indirect Method.—In this method the losses in the generator are found and the efficiency is calculated from the formula

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

The output is as before directly measured by means of a voltmeter and ammeter properly connected in the external circuit. The losses are partly calculated and partly found by experiment.

The calculated losses are those due to power spent in overcoming the field and armature resistances. In each case and for each particular part, the loss in watts is equal to the square of the current multiplied by the resistance, or

$$\text{watts} = C^2R.$$

Thus, for the

armature loss, $W = C^2_a r_a;$
series-field loss, $W = C^2_m r_m;$
shunt-field loss, $W = C^2_s r_s;$ etc.

The losses found by experiment are those due to

Friction of the bearings, brushes, air friction.
Eddy currents in the armature core.
Hysteresis losses in the armature core.

These losses can be determined by running the generator as a motor with no load, separately exciting the field to its normal extent and supplying the armature with current sufficient to make it run at the same speed it did when running as a generator; or, in other words, sufficient to impart to the armature terminals an E. M. F. equal to the *total* E. M. F. generated when run as a generator.

The efficiency of a motor is the ratio of the input to the output, or

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}}.$$

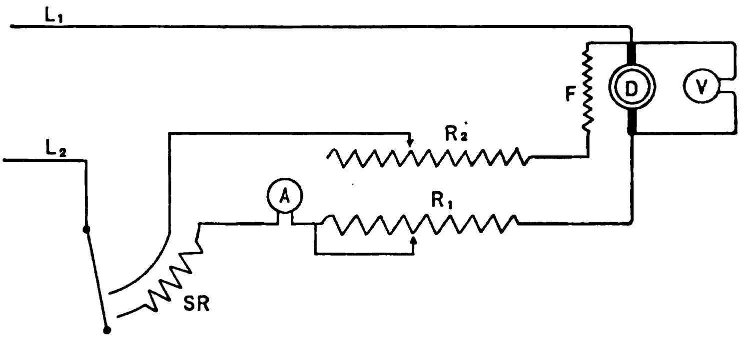


FIG. 135.—Connections for Swinburne's Test.

When the generator is run as a motor with no load and separately excited, the efficiency is zero, or

$$\text{input} = \text{losses}.$$

The losses now are the watts lost in the armature, due to the current producing the speed and the other losses referred to. The current and the armature resistance both being so small, the $C^2_a r_a$ is so extremely small as to be negligible, so the input is equal to the losses due to friction, hysteresis and eddy currents.

The input is measured by a voltmeter connected to the armature terminals and an ammeter connected in the circuit.

Swinburne's Test.—The connections for finding the current absorbed when supplied with an E. M. F. equal to that produced as a generator is shown in Fig. 135 and is known as Swinburne's test.

Connections are made as in Fig. 135, in which

L_1L_2 are the supply mains,
D the armature under test,
F the shunt-field coils,
R_1 adjustable resistance for varying voltage at armature terminals,
R_2 adjustable resistance for regulating exciting current,
V voltmeter connected across armature,
A ammeter for measuring armature current,
SR starting rheostat.

Instruction.—With the resistance in R_2 all out, close the switch of SR. This throws in the shunt field and excites it and at the same time sends current through R_1 and the armature D, starting it.

Adjust the resistance in R_1 until the voltage shown on V is equal to that produced when running as a generator. (Note that this E. M. F. must be the total E. M. F. produced, calculated for a shunt generator from $E = e + C_a r_a$, or $E = e + (C + C_s) r_a$.) Measure the speed. If it is not the same as that for which E was calculated, adjust R_2 until the proper speed is obtained.

When running at the proper speed and the voltmeter shows the proper E. M. F. read A, and call it C_A.

The calculation of losses is as follows, the data known from running as a generator being e, C, r_a, r_s:

$$C_s = \frac{e}{r_s},$$

$$E = e + (C + C_s) r_a,$$

$$C_a = C + C_s.$$

Loss in armature $= C^2_a r_a$,
" shunt $= C^2_s r_s$,
" driving $= E \times C_A$.
Total losses $= C^2_a r_a + C^2_s r_s + EC_A$.
Output $= eC$,
Input $= eC + C^2_a r_a + C^2_s r_s + EC_A$.

$$\therefore \text{ Efficiency } = \frac{eC}{eC + C^2_a r_a + C^2_s r_s + EC_A}.$$

This method is applicable to shunt, series or compound generators,

the only difference being in the calculation of the losses in the armature and field, as the current flowing in them will be different in each class of machine.

This indirect method can best be illustrated by an example. A *short*-shunt compound generator maintains a difference of potential at the terminals of 150 volts at a certain speed and supplies 20 amperes to the external circuit. The resistances are

Armature,	.18 ohm,
Series winding,	.07 ohm,
Shunt winding,	.95 ohm.

Solution: The fall of potential in the series winding $= 20 \times .07 = 1.4$ volts; therefore, the difference of potential at armature terminals $= 150 + 1.4 = 151.4$ volts.

$$\text{Shunt current} \quad = \frac{151.4}{95} = 1.59 \text{ amperes,}$$

$$\text{Armature current} = 20 + 1.59 = 21.59 \text{ amperes.}$$

The fall of potential through armature $= 21.59 \times .18 = 3.9$ volts.

When this machine was connected to run as a motor as in Fig. 135, it was found, when running at the same speed as before, that to produce the total E. M. F. $150 + 3.9 = 153.9$ volts it required .75 ampere.

$$\begin{array}{lcllcrl}
\text{Loss in armature} & = & 21.59^2 & \times .18 & = & 84.8 & \text{watts.} \\
\quad \text{"} \quad \text{shunt} & = & 1.59^2 & \times 95 & = & 240.3 & \text{"} \\
\quad \text{"} \quad \text{series} & = & 20^2 & \times .07 & = & 28.0 & \text{"} \\
\text{Other losses} & = & 153.9 & \times .754 & = & \underline{116.0} & \text{"} \\
\text{Total losses} & & & & = & 469.1 & \text{"} \\
\text{Output} & = & 20 \times 150 & & = & \underline{3000\ \ } & \text{"} \\
\text{Input} & = & & & & 3469.1 & \text{"} \\
\therefore \text{Efficiency} & = & \frac{3000}{3469} & = 86.4 \text{ per cent.} & & &
\end{array}$$

Commercial Efficiency of Motors.—The commercial efficiency of a motor is the ratio of the mechanical power of the motor to the electrical power supplied to it, both amounts of power being expressed in the same units.

The electrical power supplied to the motor is expressed in watts and is found from the readings of a voltmeter and ammeter properly connected to the supplying circuit.

The mechanical power is usually expressed in terms of horsepower, one horsepower being 33,000 foot-pounds per minute or equal to 746 watts.

The ordinary mechanical means of measuring the power given out by a motor is by some form of brake, or by dynamometer.

Brakes.—Brakes may be of several kinds, the ordinary ones being the *band* brake and *arm* brake.

In the **band** type, the brake is applied directly to a rotating pulley on the motor armature shaft, the pull exerted by the brake being on the surface of the pulley and tangential to it.

In the **arm** brake, the brake is connected to an arm and the pull is exerted at the end of the arm, the brake itself being on the surface of the pulley.

Formula for Brake Horsepower.—Power is the rate of doing work, or the rate of overcoming a force in a given distance.

In the case of a brake, the force overcome is that exerted at the surface of the pulley, due to the turning force of the motor, and is overcome by the friction between the brake and the pulley.

Let $f =$ force in pounds exerted by the brake,
$d =$ diameter of pulley in feet,
$n =$ number of revolutions per minute.

The distance per revolution is πd feet, and the work done in n revolutions is $fn\pi d$ foot-pounds, and the power exerted is $\frac{fn\pi d}{33{,}000}$ horsepower.

If the arm brake is used, the force exerted by the brake at the end of the arm is fl, where l equals the length of arm in feet; and the horsepower is $\frac{fln\pi}{33{,}000}$.

Dynamometers.—In all types of brakes, in order to measure the power given out, it is absorbed, but this absorption is not necessary, if some means is provided of measuring the torque.

The torque is the force exerted at the rim of a pulley on the motor shaft and measures its tendency to turn round its axis. Numerically it is equal to the force $\times$ the radius of the pulley. The power given out is the product of the torque and speed. The speed is $2\pi n$ feet per minute and the power is

$$fr2\pi n \text{ or } fdn\pi \text{ foot-pounds.}$$

Dynamometers are contrivances for measuring torque and are of two general kinds, **transmission** and **absorption** dynamometers.

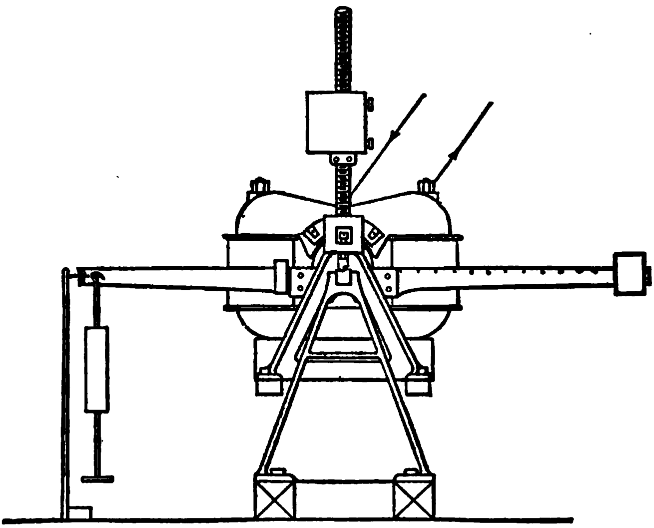


FIG. 136.—Brackett's Cradle Dynamometer.

Brackett's Cradle.—This form of absorption dynamometer is shown in Fig. 136.

The motor is bolted to a small platform which is suspended on a pair of knife edges fixed in a frame, one at each end of the cradle in line with the center of the motor shaft when the latter is properly placed. The cradle has a swinging motion about the axis of the knife edges but is otherwise rigid.

The cradle is fitted with lugs to which may be secured a graduated arm, on which slide known weights. On the cradle are

upright screws on which work different weights, fitting eccentrically on the screw shafts, and by these, the center of gravity of the system may be made to coincide with the axis of suspension, and the cradle can be accurately balanced.

If necessary a belt or cord may be passed around the motor pulley and drawn taut, so as to produce a braking effect to reduce the revolutions, but without tending to disturb the balance on the knife edges.

Measuring the Output.—When the motor is accurately balanced with the weight at the zero of the scale, current may be supplied to the motor. The field will tend to rotate relative to the armature, due to the drag on the armature conductors, and this drag will pull the motor around. It can be brought back to its level position by moving the weight out on the arm, or different weights may be used at different distances to produce the balance.

The torque is equal to the product of the weight and the distance it is from the center of the shaft, or in case more than one weight is used, it is the sum of the products of each weight by its own distance.

As shown above the power exerted, or given out by the motor is

$$\frac{fdn\pi}{33{,}000} \text{ horsepower,}$$

where $f =$ weight on the arm in pounds,
$d =$ distance of weight from center in feet,
$n =$ revolutions of armature per minute.

It is not necessary that the weight shall be at zero when the motor is balanced, but it should be noted where it is, and then knowing the distance it has to be moved to obtain a balance, the torque is the product of the weight and the distance it has been moved.

It is also not necessary that the zero of the scale should coincide with the center of the shaft, for when the first balance is effected, the moment of the weight about the center is counterbalanced by the adjusting weights, so the zero mark of the scale can be placed at any convenient place on the arm.

Determination of Losses.

In the preceding remarks regarding efficiency, it was shown that the difference between the input and output of dynamo electric machines was due to the losses in the machine; and expressed as watts, the loss is equal to the input minus the output, both of course being expressed in watts.

The losses are of two distinct classes; those due to the heat produced in the armature and field windings, produced by the currents flowing through the resistances; and the others due to the heat produced by eddy currents in the iron core of the armature, the hysteresis loss in the same, and the heat caused by friction in the bearings, by the brushes, air friction, etc. The first of these are generally referred to as *copper losses* and are easily calculated, the others are called *iron* and *friction losses.*

The separation of these losses is of greatest importance to the designer, and tells him how best to reduce the total loss. Excessive hysteresis shows inferior quality of iron in the armature core, and large eddy currents shows poor lamination in the core. Large friction losses show inferior lubrication, and possibly improper contact of brushes.

The separation of the iron and friction losses is given here for purposes of experiment, as such work is of great help in procuring a sound understanding of the entire principles governing the construction of electric machines.

Determination of Iron and Friction Losses.—For this experiment make connections as shown in Fig. 135 with the addition of an ammeter in the field circuit, the machine under test to be run as a motor without load. When this is the case there are no copper losses, except the extremely small loss due to the current necessary to drive the armature, which may be neglected as being less than one watt, and all the losses are those due to iron and friction.

The experiment is similar to that for finding the efficiency of a generator (the indirect method) but more observations are taken.

Instructions.—Run the machine for some time (one or two hours) to get everything running smoothly and conductors warmed to a normal extent.

Excite the field to its normal extent, that is by the same current it would have when running at normal speed as a generator. By means of the adjustable resistance R_1 (Fig. 135) get a small voltage at the armature terminals, and with the exciting current constant, take readings of the armature voltage, armature current and speed.

Always keeping the exciting current constant, increase the armature voltage, then make same readings as before. Do this for gradually increased voltage till the full voltage is obtained.

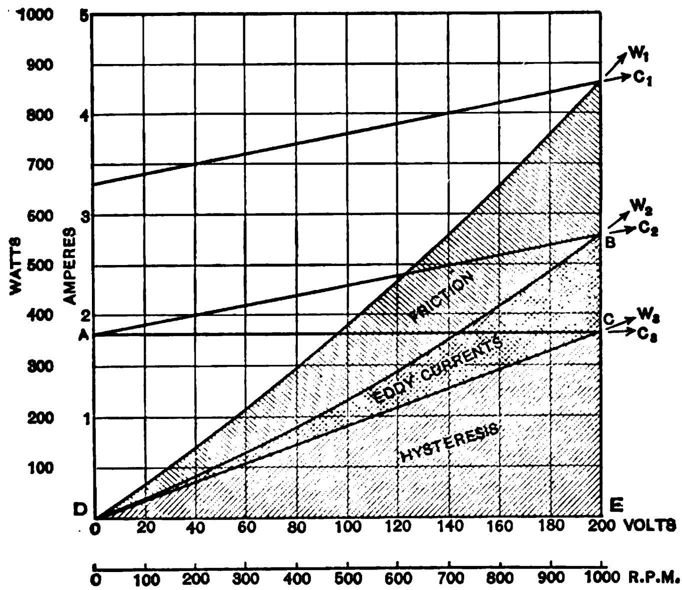


FIG. 137.—Curves Showing Separation of Losses.

Construction.—With the two variable quantities, armature voltage and armature current, plot points to some convenient scale, making volts as abscissæ and amperes as ordinates and draw a curve through the points so determined.

Such a curve is shown in Fig. 137 marked C_1.

As the armature current is directly proportional to the voltage at the terminals, the relation between the current and voltage is

constant and therefore the equation to the curve is of the form $y = mx + c$, c being the distance the line starts above the axis of volts.

Since the speed and voltage are proportional with a constant excitation, a scale of revolutions per minute may be added. In the example assumed 1000 revolutions per minute correspond to 200 volts.

The iron and friction loss, or **no-load loss curve** can now be plotted. This is done by plotting the volts as abscissæ and the product of volts and amperes as ordinates, a scale of watts being marked to a convenient scale on the left. Thus for volts equal to 40, the current is 3.5 amperes, and the watts $40 \times 3.5 = 140$. This is plotted with 40 as abscissa and 140 as ordinate. Similarly other points on the curve are plotted and the curve W_1 drawn through them.

The ordinates of this curve for any speed will show the "no-load" loss at that speed.

Determination of Friction Losses.—The loss due to friction of the brushes and of the bearings increases in direct proportion to the speed of the armature, while the air-friction loss varies almost as the square of the speed.

If the armature could be run without any field, there would be no iron losses, and the only loss would be that due to friction, so the method employed to determine the friction loss is to estimate the power required to run the armature without field.

By observing the current and voltage necessary to keep the speed constant, a curve of watts can be plotted to show the no-load loss over a considerable range of field excitation. These curves can be plotted for different speeds and then an estimate can be made of what the losses for different speeds would be if the field excitation was zero, which would be the reading of the watts for zero voltage; found by prolonging the curves for the speeds until they cut the axis of watts.

A set of these curves are shown in Fig. 138 in which the same scale is used as in Fig. 137, but are plotted separately to avoid confusion.

The data for these curves is found by using the same connections

as in the previous experiment and shown in Fig. 135. The excitation of the field is varied by the resistance R_2 and the armature voltage is adjusted to maintain the speed constant by adjusting R_1. For the given speed take reading of the exciting current, armature volts and amperes. Reduce the exciting current, keeping the speed constant by R_1 and take readings as before. Repeat this operation for the constant speed, reducing the exciting current to as low value as can be employed.

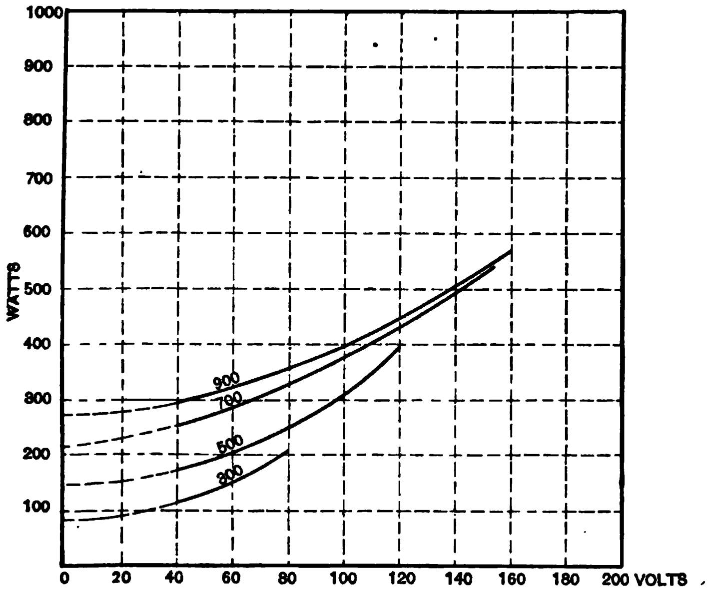


FIG. 138.—Curves of No-Load Loss.

With a new speed, repeat the operation, getting as many points on the curve as possible, especially with the low exciting current.

For each set of observations, one set for each speed, find the watt curve or the product of armature volts and amperes, and with the volts as abscissæ and watts as ordinates, plot a series of points for each speed, and through these points draw fair curves.

The ordinates of these curves for any armature voltage will give the "no-load" loss for the different speeds.

These curves are continued until they cut the axis of watts at zero voltage, in which case the ordinates at zero voltage will give the friction losses for those speeds.

Remembering that the curve W_1 (Fig. 137) represents the total no-load loss, the friction losses found from the curves on Fig. 138 can be transferred to it, and subtracting the friction losses from the total loss for the corresponding speed, the remainder will be the total iron losses. This will give curve W_2, the ordinates intercepted between curves W_1 and W_2 being the friction losses for the different speeds or different armature voltage.

From curve W_2, which is the **watt curve of iron losses,** the current curve C_2 can be plotted by dividing each ordinate (watts) by the corresponding abscissæ (volts), using for points on the curve, volts for abscissæ and amperes for ordinates. This curve will be a straight line for the same reason as given for curve C_1.

Where the curve C_2 cuts the axis of watts, draw a horizontal line C_3. This line divides the ordinates of the current line C_2 into two parts, the portion below the horizontal line representing the current required to overcome the hysteresis loss, and the portion intercepted between the horizontal line and curve C_2, the current required to overcome eddy-current losses.

The area of the triangle $ABC = \frac{1}{2} BC \times AC$,

$$\frac{BC}{AC} = \tan a, \quad \therefore \text{ area} = \tfrac{1}{2} AC^2 \tan a,$$

and is therefore proportional to the square of the voltage and consequently to the square of the speed. Since eddy losses increase in proportion to the square of the speed, the area must represent the power necessary to overcome them. The area $ACED$ is proportional to DE, $\therefore$ to the voltage and to the speed, and as hysteresis is proportional to speed, this area represents the power necessary to overcome the hysteresis loss.

From the last curve C_3, find the watts spent in overcoming hysteresis, by multiplying the current ordinate by any voltage within the limits of experiment, and drawing a straight line through this point to the origin.

The losses are now completely separated and are as shown in Fig. 137. The friction losses are represented by the ordinates for

any voltage (or speed) between the two curves W_1 and W_2; the eddy-current loss by the ordinates between W_2 and W_3 and the hysteresis loss by the ordinates between W_3 and volt line, and the sum of course equals the total friction and iron loss for any voltage.

Example.

The foregoing separation of losses may be made clearer by an example with assumed values to illustrate the experiment, the values taken being those used to plot figure 137.

In the first part of the experiment, keeping the exciting current constant and varying the voltage, the following values were obtained in columns I and II.

I. V (volts).	II. C (amperes).	III. VC (watts).
40	3.5	$40 \times 3.5 = 140$
80	3.7	$80 \times 3.7 = 296$
120	3.9	$120 \times 3.9 = 468$
160	4.1	$160 \times 4.1 = 656$
180	4.3	$180 \times 4.3 = 860$

Curve C_1 was plotted with the values given in columns I and II, and curve W_1 with values in columns I and III.

In the second part of the experiment, the friction loss, the following data was obtained by keeping the speed constant for a series of readings and observing the armature volts and amperes, the observed data being given in the second and third columns of the four tables, *A*, *B*, *C* and *D*.

A				B			
I. Revs.	II. V.	III. C.	IV. VC.	I. Revs.	II. V.	III. C.	IV. VC.
900	160	3.6	576	700	160	3.6	576
900	120	3.8	456	700	120	3.6	432
900	80	4.5	360	700	80	4.2	336
900	40	7.5	300	700	40	6.5	260

C				D			
I. Revs.	II. V.	III. C.	IV. VC.	I. Revs.	II. V.	III. C.	IV. VC.
500	120	3.3	396	300	80	2.6	208
500	80	3.1	248	300	40	3.0	120
500	40	4.5	180				

The four curves of Fig. 138 were plotted from the data of columns II and IV.

These curves were then prolonged until they cut the vertical axis, the ordinates of which gives the friction loss in watts. These values are from the curves:

Revs.	Friction watts.
900	270
700	210
500	150
300	90

To Plot Curve W_2.—On ordinate corresponding to speed of 900 revolutions subtract the friction loss for that speed, thus

For 900 revolutions	(180 volts)	$755 - 270 = 485$
700 "	(140 ")	$560 - 210 = 350$
500 "	(100 ")	$380 - 150 = 230$
300 "	(60 ")	$215 - 90 = 125$

With the values in the last column of the above table and volts corresponding to the speed of the first column, plot curve W_2.

To Plot Curve C_2.—Divide the values in the last column of the above table by the voltage corresponding to the speed, thus

VC.	V.	C.
485 ÷	180 =	2.7
350 ÷	140 =	2.5
230 ÷	100 =	2.3
125 ÷	60 =	2.1

With the values of V and C of the above table, plot curve C_2. This will be a straight line parallel to C_1 for the differences of their ordinates is a constant quantity; thus ordinate of C_1 corresponding to 180 is 4.2, to 140 is 4.0, to 100 is 3.8 and 60 is 3.6. The differences of the ordinates is then

$$4.2 - 2.7 = 1.5$$
$$4.0 - 2.5 = 1.5$$
$$3.8 - 2.3 = 1.5$$
$$3.6 - 2.1 = 1.5$$

To Plot Curve C_3.—This has already been explained.

To Plot Curve W_3.—The ordinate of C_3 is the difference between that of C_1 for zero voltage and the differences of the ordinates of C_1 and C_2, or $3.3 - 1.5 = 1.8$ amperes.

For 20 volts then the watts are equal to

	20×1.8	amperes	=	36	watts,	
and	40×1.8	"	=	72	"	
"	60×1.8	"	=	108	"	
"	80×1.8	"	=	144	"	
"	100×1.8	"	=	180	"	etc.

As there is a constant difference the line is straight and can be determined by taking any convenient voltage, finding the watts, and plotting the point with volts and watts and drawing a straight line to the origin.

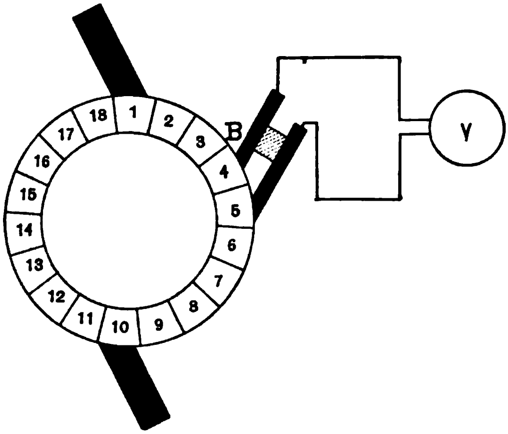


FIG. 139.—Exploring E. M. F. Around Armature.

Determination of E. M. F. Around Armature.

The object of this test or experiment is to show the distribution of potential differences around the armature. If the difference of potential is measured between the negative brush and successive bars of the commutator it will be found that in a well-designed machine the difference of potential increases regularly, though not equally, in both directions, becoming a maximum when the position of the positive brush is reached. In badly-designed machines the distribution will be found to be irregular.

One way of attaining the differences of potential is to measure the voltage induced in the coils connected between individual pairs of commutator segments at different points around the circumference. There are two methods in general use of making these measurements, depending on the relative position of the individual pairs of commutator segments to which the measuring instrument is connected.

Two-Brush Method—S. P. Thompson Method.—If the difference of potential between successive segments is required the simplest method is to use two small brushes insulated from each other and fixed apart a distance equal to that between successive commutator

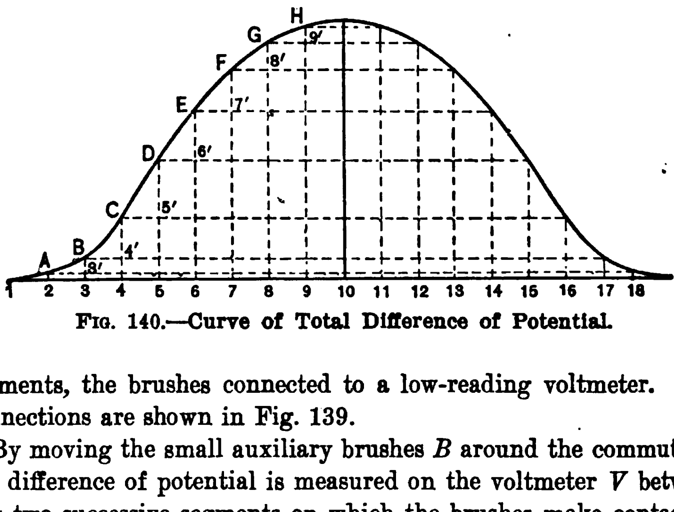


FIG. 140.—Curve of Total Difference of Potential.

segments, the brushes connected to a low-reading voltmeter. The connections are shown in Fig. 139.

By moving the small auxiliary brushes B around the commutator the difference of potential is measured on the voltmeter V between any two successive segments on which the brushes make contact.

The results may be plotted in the form of a curve which will show the total difference of potential between brushes or between one brush and any particular segment as well as the difference of potential between successive segments. Such a curve is shown in Fig. 140.

In Fig. 140 the position of the negative brush is shown at 1 and the positive brush at 10, and the commutator segments are numbered consecutively from 1 to 18. If the exploring brushes are pressed against segments 1 and 2, the resulting E. M. F. would be

plotted, according to some convenient scale, as an ordinate equal to $2 - A$. If connected to 2 and 3, the resulting E. M. F. is plotted as $3' - B$. To this must be added that due to $1 - 2$, which is $3 - 3'$. In other words, following consecutively around the commutator, the resulting E. M. F. should be added to the total E. M. F. up to that point, and in this way the whole curve is constructed; after leaving the positive brush, the resulting differences of potential will be subtractive from the preceding one.

Single-Brush Method—Mordey's Method.—A more general method of attaining the same result is to use only the auxiliary contact brush, to which the terminal of the voltmeter is connected, the other terminal being connected to one of the main brushes of the machine. By moving the auxiliary brush from one segment to another, the difference of potential is measured from the machine brush to the segment, and to obtain the difference between any two segments it is only necessary to subtract the differences of potential between the main and auxiliary brushes, when the latter is connected to consecutive segments.

In using two auxiliary brushes, the voltmeter may be a low-reading one, as the greatest difference of potential is only that between two successive coils, but the single-brush method requires a voltmeter to register the complete voltage of the armature.

The results obtained by the single-brush method can be plotted in a curve exactly similar to that shown in Fig. 140. When the auxiliary brush is connected to segment 2 the resulting voltage can be plotted as $A - 2$; when on segment 3 as $3 - B$, etc.

To obtain the difference between any two consecutive segments, or in fact, any two segments, it is only necessary to subtract the ordinates corresponding to the segments desired.

Practical Arrangement of a Single-Brush Method—Joubert's Method.—A practical method devised by Joubert for examining the E. M. F. induced at successive points on the commutator is shown in Fig. 141.

D and *E* are two wooden discs fitted around the armature shaft and can be secured in any position relative to each other. One of these is fixed to the shaft and the other is carried by it. The disc *E* is fitted with a continuous metal rim to which is connected a

small spring F which presses against the commutator. Let into the rim of B is a contact plate C which has a small tongue which is in contact with the metal rim of E. The auxiliary brush B is fixed and rubs against the rim of D, making contact with C once in each revolution.

When C passes under the brush B, the circuit is completed through the voltmeter V. By shifting D and E relatively to each other, C and F are brought relatively nearer together or further apart, so connection can be made between any two segments of the commutator. This device can be so arranged that when C is pass-

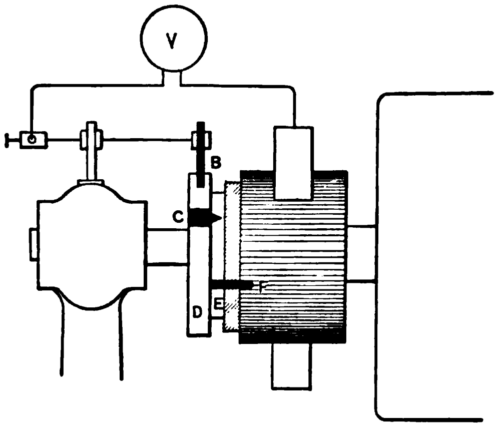


FIG. 141.—Illustrating Joubert's Method of Exploring E. M. F.

ing under B, F makes contact with the adjoining segment to that under the main brush of the machine, so the voltage obtained will be that between the main brush and its adjoining segment. By shifting F ahead the angular distance of one segment at a time, the voltages will be measured consecutively around the commutator from the common brush.

Owing to the fact that the contact of the brush B with the contact piece C is momentary and intermittent, an ordinary voltmeter would oscillate rapidly, or if it was absolutely dead beat, it would indicate a mean lower voltage than that corresponding to the voltage at the instant of contact. For accurate results, it is better to use

an electrostatic voltmeter with a condenser connected in parallel, as the voltmeter would probably have so small a capacity that it would discharge itself too rapidly to affect the slow-moving needle. A hot-wire voltmeter specially calibrated can be used to good advantage.

In making the test, it is well to connect another voltmeter to the machine terminals, and by means of a regulator in the shunt field, keep the voltage of the machine constant during the test.

One experiment can be made with no load on the machine and another with full load, and the differences in the resulting curves

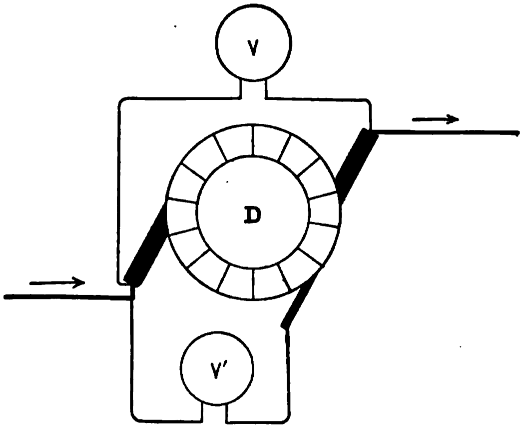


FIG. 142.—Fall of Potential Around Armature.

of E. M. F. will show the effect of the armature current on the field distribution.

Fall of Potential Around a Stationary Armature.—In the above methods, the fall of potential around the commutator has been measured by the current produced by the armature itself, but to test the similarity of windings in the different sections of an armature, an outside source of current can be used and the fall of potential due to the resistance of the armature windings can be tested.

Connections are made as in Fig. 142.

The brushes of the stationary armature *D* are connected to an

outside source of current and a strong current is sent through the armature and a voltmeter V connected to the brushes will show the total fall of potential through the armature windings. Another voltmeter V' is shown connected one terminal to one brush, the other to any segment of the commutator.

If the armature is sound and the windings similar there should be the same fall of potential from the leading-in point to segments each side equally distant from it, and the fall of potential should be the same from one segment to another. If it is not, it indicates a fault of some kind in the winding, and this method can be used to locate short circuits, as a short-circuited coil would show no change of difference of potential from its adjoining coil.

CHAPTER XVIII.

INCANDESCENT LAMPS.

When a current of electricity is urged through a conductor, heat is developed, the amount of heat being proportional to the amount of energy expended in the conductor. If a current C is forced through a resistance R for a time t, the number of joules, or electrical units of heat developed, is C^2Rt.

The distinction between heat and temperature must be kept in mind. The same amount of heat may be applied to two conductors, and the resulting temperature be widely different. When a conductor is made very hot, or has a high temperature, it becomes luminous and the luminosity is proportional to the temperature. Suppose there were two conductors A and B of same sectional area, and B twice as long as A, and therefore twice its resistance, and equal currents urged through both. The energy expended in A, or the heat developed will be only half that in B, but the temperatures will be equal, as B has twice as much matter as A. The luminosity of these two conductors will be the same, although B absorbs or requires twice as much energy as A. Suppose, however, the conductors are the same length, but B is given the same resistance as before by halving its cross-sectional area. With the same currents as before, B still absorbs twice as much energy as A, and twice as much heat will be developed in B as in A. Since the mass of B is only one-half that of A, equal quantities of heat would cause the temperature of B to be twice that of A, and since twice as much heat is developed in B, its temperature is raised to four times that of A, and therefore its luminosity is four times as great for the same current.

This shows that to obtain great luminosity a large amount of energy must be expended on a small mass of matter, and the mass must be kept small by reducing the area of cross-section rather than by increasing its length and the material should have a high specific resistance. Enough heat may be absorbed by a con-

ductor of small mass to raise its temperature to such a degree that it may become luminous, and if the heat produced by the current is not radiated as fast as produced, the temperature will reach the melting point, and the conductor, or portion of it, will be destroyed by uniting with the oxygen of the air. If the conductor was heated to incandescence before burning up and it could be kept in such a state, then we would have an incandescent lamp.

To prevent its uniting with oxygen, the resistance of an ordinary incandescent lamp is secured in a glass bulb from which almost all air and other gases have been exhausted.

Manufacture of Lamps.

The materials which have been tried in the incandescent or glow lamp are platinum, osmium, iridium, an alloy of platinum and iridum, carbide of titanium, tantalum, tungsten and carbon. Of these, carbon is the substance almost universally employed, its chief advantages being: (1) That after the temperature of incandescence is reached, the luminous rays increase more rapidly than the heat rays for further increases of temperature than is the case with metals. (2) Its temperature of volatilization is higher than that of metals. The temperature at which metals emit light is not much less than their melting points, while carbon has no actual melting point, but a temperature of volatilization higher than that needed for incandescence. (3) The cross-sectional area of carbon can be made more nearly uniform than is possible with metal wires.

The complete manufacture of an incandescent lamp requires from thirty to forty distinct operations, the principal of which are given in the following description:

The **filament** is the chief feature of all glow lamps and upon its manufacture depends the success and behavior of the completed lamp. In nearly all cases, the filament is made from cellulose, a transparent, gelatinous hydrocarbon. This cellulose is prepared in different ways as follows:

1. Treating pure cotton wool to a washing and boiling operation to remove any "dressing," dirt or foreign material obtained in the course of its manufacture. After drying, the wool is wound loosely around two opposite sides of a rectangular glass frame of such a

size that each ply is a little longer than the length of the completed filament. The cotton thus wound is immersed in a clear solution of pure concentrated sulphuric acid and pure water of proportions 2 to 1. This operation only takes a short time and is complete when the last traces of the strands of cotton disappear, after which the frame is immersed in clear running water. It is next immersed in a one per cent solution of ammonia and water to remove all traces of acid and again washed in clear water. The cotton has been transformed into the transparent, gelatinous substance known as cellulose.

2. The purest cotton wool is heated with a solution of zinc chloride in which it dissolves, forming a syrupy mixture from which is precipitated by alcohol a hydrated cellulose zinc oxide. The solution is treated with hydrochloric acid which liberates the zinc, after which it is washed and the solution is reduced to cellulose by ammonium sulphide. The fluid result is a brownish liquid of about the consistency of molasses.

3. Special kinds of paper are chemically treated in such a way as to produce a thick solution of cellulose.

Forming the Filament.—After the thick gelatinous mass of cellulose has been obtained, the desired form of the filament is made while it is still in a pliable condition. The solution is forced by light pneumatic pressure through orifices or dies, made of sapphire-agate stones which contain holes of diameters corresponding to the area of cross-section desired. The cellulose issues from these holes in a continuous thread and is allowed to coil in glass jars filled with alcohol which acts to set and harden it. This thread is allowed to remain until all traces of the zinc chloride disappear when the thread now resembles fine cut catgut and is tough and flexible. It is washed well to remove all traces of chemicals and is then ready for shaping.

The filaments are **shaped** by winding the thread over "formers" of carbon, according to the desired shape of the completed filament. These are then lightly baked to ensure the shape being retained. Such a shape is shown in 2, Fig. 143.

Carbonizing the Filament.—After forming, the thread is removed from the formers and is closely packed with powdered carbon

in graphite crucibles. These crucibles are then placed in a coke furnace and brought gradually to a white heat, at which temperature they are kept for a day or two when they are allowed to slowly cool. This operation converts the threads into pure carbon of a dull black color. The threads are then measured for diameter by micrometer calipers, measuring to $\frac{1}{10000}$ inch and sorted according to diameters.

The next step in the process of manufacture is the **flashing** process, and the arrangement for doing this varies in different factories. In general it consists in raising the filament to a high degree of incandescence while it is an atmosphere of some hydrocarbon vapor such as gasoline or benzine. The thinner portions of the filament become hotter than the rest which causes the carbon in the vapor to be deposited in greater quantity at those points, as well as in every little hole in the filament, and thus causing the filament to become of uniform cross-section throughout.

In some processes, the filament is hung in an air-tight vessel containing the hydrocarbon, which vaporizes and surrounds the filament; in others, the vessel is fitted with two orifices, by which air may be exhausted from one and vapor admitted at the other. This method insures the rapid volatilization of the liquid hydrocarbon. While surrounded by the vapor, the filament is connected either to a generator or a storage battery and heated to incandescence, the operation being repeated several times. As the carbon is deposited the resistance decreases and the current increases, and automatic arrangements are made by which the current is shut off when the desired resistance has been attained.

The color of the filament has now changed to a steel gray and is coated uniformly with finely divided, hard and compact carbon. It is now ready for connection to the plug.

Small copper wires, such as shown in 1, Fig. 143, are attached to two platinum wires, each about $\frac{1}{2}$ inch in length, by heating and fusing the two together. This combination of wires is then assembled in a glass tube (3, Fig. 143), the platinum wires being fused in the glass (4, Fig. 143). Platinum is used because it does not fuse at the temperature necessary for fusing the glass, and its coefficient of expansion is about that of glass, so there is no

danger of leakage of air into the exhausted bulb due to unequal expansion.

The filaments are then attached to the platinum wires by a carbon paste or cement which is carbonized by passing a current through the filament. The completed filament is shown at 5, Fig. 143, and is then ready for attachment to the glass bulb.

The Bulb.—There are no peculiarities in the construction of the bulbs, which are blown to the proper size and shape (7, Fig. 143).

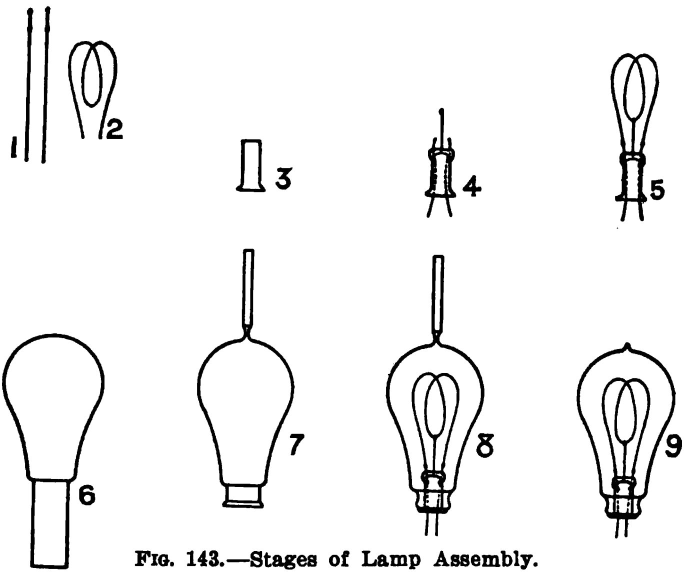


FIG. 143.—Stages of Lamp Assembly.

The glass tube holding the filament is secured in the mouth of the bulb and the edges are fused to the edge of the bulb (8, Fig. 143).

Exhausting the Lamp Bulb.—It is of the utmost importance to secure a good vacuum inside the bulb, for the efficiency as well as the life of a lamp depends upon the goodness of the vacuum. The poorer the vacuum the greater the conduction of heat from the filament to the bulb and to the outside atmosphere, so that the energy absorbed by the filament is not given as temperature to the filament and the efficiency is reduced.

The life is shortened due to the disintegration of the filament

which is made manifest by the blackening of the inside of the bulb by the deposition of carbon on it.

The bulb is connected to an air-suction pump, as the Sprengel mercurial pump. When the vacuum has attained a steady value, current is sent through the filament so as to heat it to redness and gradually increased to about 25 per cent above the normal incandescence. This drives out any air that may be held in the filament, the pump kept going all the time. When the desired vacuum has been attained, the glass tube blown in the bulb and by which it is connected to the tube leading to the pump is gradually heated near the bulb until the glass softens. The bulb is gradually pulled away and the softened glass of the tube draws together and gradually closes the opening and a final twisting motion seals the bulb leav-

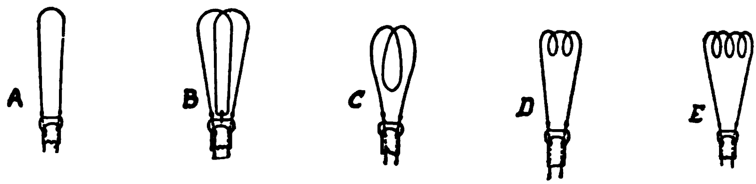


FIG. 144.—Types of Filaments.

ing the little sharp nipple seen on all glow lamps. The lamp as now completed is shown in 9, Fig. 143.

The Base Attachment.—The standard Edison base consists of a threaded brass open-ended cylinder, perforated with a hole near the middle of its length, and of a brass disc perforated through its center. The copper leading-in wires of the completed combination shown in 9, Fig. 143, are threaded through the holes, one in the cylinder and one in the disc. The whole cylinder is then filled with plaster of paris and when this sets, the ends of the wires are trimmed off and soldered at the perforations.

In a method using a glass plug in place of plaster of paris, the plug is made of molten glass poured in the base, after which the contact is secured by a rivet. The other leading wire is soldered at the top of the base.

The types of filaments used in naval incandescent lamps are shown in Fig. 144, and the lamps with which they are used are given in the table on page 375.

Candle-Power of Incandescent Lamps.

Lamps are rated and marked at so many candle-power, the standard now used in the service being 1, 2, 5, 6, 10, 16, 32 and 150 candle-power. For ordinary illumination 16-candle-power lamps are used, those of 5 candle-power being used in store-rooms and passages below decks, those of 32 candle-power in the night signal system, running lights, truck lights and anchor lights, and those of 150 candle-power for general illumination in open spaces, where a large amount of light is needed for night purposes and in the diving lamp—these generally being used in portable fixtures. Lamps of 1, 2, 5 and 10 candle-power are used in instruments and telephotos, and the 6 candle-power for torpedo lamps.

Standard Lamp.—A 16-candle-power lamp is one that will give the same intensity of light, or the same amount per unit of area as sixteen standard candles, or an intensity sixteen times as great as one standard candle; a standard candle being a spermacetic candle $\frac{7}{8}$ of an inch in diameter, burning 120 grains per hour. The practical unit of white light is the quantity of light emitted normally by a square centimetre of surface of molten platinum at the temperature of solidification.

Comparison of Lights.—Incandescent lamps are compared with a standard candle by means of photometers, these being instruments by which the amount of light falling on a given surface may be measured, or by which the effect of light from two sources is neutralized, and the intensities of the two lights compared. The intensity of light from a given source is determined by the physical law, *that the intensity of light received by an object varies inversely as the square of its distance from the source of light.*

All lamps have marked on them the voltage necessary to produce the rated candle-power. A lot of lamps made at the same time, by the same process and by the same workmen with the same care will not all give the same candle-power for the same voltage. Instead of considering the voltage constant and determining the candle-power, the candle-power is regarded constant, and the voltage necessary to produce that candle-power is determined and marked on the lamp. Lamps are tested for candle-power in connection with the photometer in a horizontal position, that is, the

lamps themselves hang vertically with the loop of the filament opposite and on a level with the spot on the photometer to be illuminated, and the candle-power thus obtained is called the *horizontal candle-power*. As the candle-power thus obtained would be different from that determined in any other position, it is necessary to find what is called the mean or average spherical intensity of the illumination.

The **mean spherical candle-power** is the average candle-power on the interior surface of a sphere, of which the source of light is the center.

Effect of Age on Candle-Power.—When a lamp is first connected to a circuit, the candle-power increases for a time and then begins to fall, reaching the initial candle-power at the end of about 100 hours' burning, and the decrease in candle-power is steady from that time. As the efficiency rises, the candle-power falls more rapidly. A lamp absorbing 3.5 watts per candle-power will fall to about 75 per cent of its candle-power at the end of 900 hours, and one absorbing 2.5 watts will fall to the same percentage at the end of about 300 hours.

As a lamp gets old and its candle-power and efficiency fall, it is much better after a certain point to throw it away than to continue to burn it till rupture takes place.

Over and Under Running.

As far as possible all lamps should be worked at the voltage which will give their rated candle-power. The voltage that a lamp will require is determined by the dimensions of the filament, and each filament is so constructed as to yield its standard candle-power at the highest temperature, about 2000° C., compatible with durability, and much increase of temperature would probably cause rupture of the filament. A very slight increase in the voltage produces a much greater per cent increase in luminosity, but a corresponding danger of rupture. The candle-power increases much faster than the voltage and experiments seem to show that the candle-power of a given lamp varies as the sixth power of the applied voltage or as the cube of the absorbed watts. When the candle-power is reduced one-half the power absorbed in the filament has only fallen about 20 per cent.

This consideration shows that by under running a generator, that is running at a lower speed and consequently at a lower voltage than the normal, no advantage is gained. Even a reduction of 2 per cent in the normal voltage makes itself very apparent in the amount of light emitted, and while it may act to prolong the life of a lamp the effect is neutralized by the reduced efficiency, more power being required to produce the candle-power as the voltage falls.

The effect of over running is to seriously lessen the life of lamps, an increase of 3 per cent in the voltage being sufficient to reduce the life of a lamp to one-half, and an increase of 6 per cent to one-third.

Efficiency of Incandescent Lamps.

The efficiency of a lamp is the ratio of the mean spherical candle-power to the electrical power absorbed in producing it, but is usually referred to as so many watts per candle-power. If a 16-candle-power lamp absorbed 56 watts, its efficiency would be spoken of as 3.5 watts, that is $56 \div 16$, its efficiency being $\frac{16}{56} = .286$. The electrical power absorbed is obtained by properly connecting up an ammeter and voltmeter in the lamp circuit when testing it for candle-power in the photometer, the product of the volts and amperes giving the total watts absorbed. The electrical horse-power spent on a lamp is equal to the number of watts absorbed by the lamp divided by 746. The number of heat units or calories given out per candle-power is found by multiplying the number of watts absorbed by .24 and dividing by the number of candle-power.

The question of efficiency is closely connected with the candle-power and life of a lamp. High efficiency means high voltage, high candle-power and high temperature and consequent economy but at the expense of short life, while a reduced efficiency means less economy and longer life. A lamp that is burning at a reduced candle-power yields a lower efficiency but lasts longer than one of the same type at the full power, but it is more economical to run lamps at a high than at a low efficiency. The average life of initially high efficiency lamps is short and they deteriorate rapidly in candle-power and efficiency after about 200 hours' burning.

Standard Incandescent Lamps.

The lamps manufactured for the use of the Naval Service must conform in dimensions and shapes to certain standards, these being shown in Fig. 145.

The bases for the 100, 32, 16 and 10 candle-power are of the standard form Edison base, that for the 5 candle-power is of the

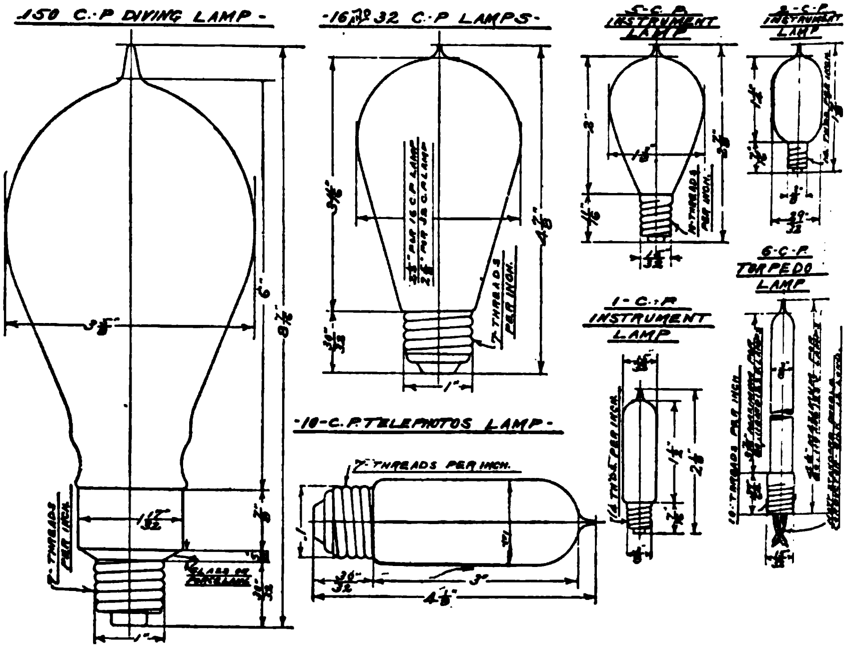


FIG. 145.—Standard Lamp Shapes.

candelabra form of Edison base. The base of the 6-candle-power torpedo lamp is fitted with leads as shown in the figure.

The bases are fitted with porcelain or glass buttons, forming the insulation between the contacts. These buttons are designed so that it is only necessary to make one channel through the button and this passes through the center of the button for the purpose of permitting the attachment of one of the leading-in wires to the contact in the center of the base. The base is firmly and accurately

fitted to the bulb with moisture proof cement. The leading-in wires and anchors are fused in the glass. These last are metal pieces secured to the loop to strengthen it and to prevent the loop from drooping when used in a horizontal position.

The filaments are centered in the bulb and in the case of the 32, 16 and 10-candle-power telephotos and 6-candle-power torpedo lamps are anchored.

Each lamp is marked to the nearest even volt that is necessary to give its rated candle-power.

1	2	3	4	5	6	7	8	9
Class.	Rated candle-power.	Standard total watts.	Type of filament.	Individual voltage limits.	Individual total watt limits.	Candle hour area at rated efficiency.	Candle hour area at 3.1 W. P. C.	Test candle-power to give 3.1 W. P. C.
SPECIAL LAMPS.								
Instrument.								
1 c.-p., 10 volts, clear.....	1	4.9	Loop........	9.25-10.75	4.5- 5.3	552	68	2.02
2 c.-p., 80 volts, clear.....	2	11	Double loop	78- 84	10.1-11.9	1,288	92	4.79
2 c.-p., 110 volts, clear....	2	13	3-coil spiral	106-116	12-14	1,472	55	6.1
2 c.-p., 223 volts, clear....	2	13	....do......	119-129	12-14	1,472	55	6.1
Torpedo.								
6 c.-p., 80 volts, clear.....	6	30	Loop........	77- 85	27-33	138	15.4	12.5
6 c.-p., 110 volts, clear....	6	30	....do.......	106-116	27-33	138	15.5	12.5
6 c.-p., 123 volts, clear....	6	30	....do......	119-129	27-33	138	15.4	12.5
Telephotos.								
10 c.-p., 80 volts, clear....	10	36	Oval........	75- 88	34-38	3,680	1,840	12.5
10 c.-p., 110 volts, clear...	10	36	....do.......	104-112	34-38	3,680	1,840	12.5
10 c.-p., 123 volts, clear...	10	36	....do.......	119-127	34-38	3,680	1,840	12.5
REGULAR LAMPS.								
Regular.								
5 c.-p., 80 volts, clear.....	5	19.5	2-coil spiral	77- 83	18-21	2,760	920	7.14
5 c.-p., 110 volts, clear....	5	19.5	....do.......	105-113	18-21	1,150	868	7.14
5 c.-p., 123 volts, clear....	5	19.5	....do.......	119-127	18-21	1,150	868	7.14
16 c.-p., 80 volts, clear....	16	56	Oval........	77- 82	53.2-58.8	12,000	8,000	19
16 c.-p., 80 volts, frosted..	16	56	....do.......	78- 83	53.2-59.8	12,000	8,000	19
16 c.-p., 110 volts, clear....	16	56	....do.......	107-112	53.2-58.8	12,000	8,000	19
16 c.-p., 110 volts, frosted.	16	56	....do.......	108-118	53.2-59.8	12,000	8,000	19
16 c.-p., 123 volts, clear....	16	56	....do.......	121-125	53.2-58.8	12,000	8,000	19
16 c.-p., 123 volts, frosted.	16	56	....do.......	122-126	53.2-59.8	12,000	8,000	19
32 c.-p., 80 volts, clear	32	115	....do.......	76- 82	109-121	20,000	11,000	40
32 c.-p., 110 volts, clear ...	32	115	....do.......	106-112	109-121	20,000	11,000	40
32 c.-p., 123 volts, clear ...	32	115	....do.......	120-126	109-121	20,000	11,000	40
Diving.								
150 c.-p., 80 volts, clear ...	150	465	2-coil spiral	76- 82	442-488	13,800	13,800	150
150 c.-p., 110 volts, clear ..	150	465	2 loop.......	106-112	442-488	20,700	20,700	150
150 c.-p., 123 volts, clear ..	150	465	...do.....	120-126	442-488	20,700	20,700	150

VALUES FOR NAVY SPECIAL LAMPS.

Description of lamp.		Rating.		Initial limits.		Average performance.
Class.	Type of filament.	Rated candle-power, mean horizontal.	Initial total watts.	Individual candle-power limits.	Individual watts limits.	Useful or effective life in hours to 20 per cent drop in candle-power at 3.1 watts per candle.
Torpedo.						
6 c.-p., 80 volts	Loop	6	30	$33\frac{1}{3}$ per cent above and $33\frac{1}{3}$ per cent below.	25 per cent above and 25 per cent below.	1
6 c.-p., 110 volts	do.	6	30	do.	do.	1
6 c.-p., 123 volts	do.	6	30	do.	do.	1
Telephotos.						
10 c.-p., 80 volts clear	Oval	10	36	25 per cent above and 25 per cent below.	17 per cent above and 17 per cent below.	160
10 c.-p., 110 volts clear	do.	10	36	do.	do.	160
10 c.-p., 123 volts clear	do.	10	36	do.	do.	160
Regular Navy instrument.						
5 c.-p., 80 volts	2-coil spiral.	5	19.5	30 per cent above and 30 per cent below.	25 per cent above and 25 per cent below.	150
5 c.-p., 110 volts	do.	5	19.5	20 per cent below and 20 per cent above.	15 per cent below and 15 per cent above.	100
5 c.-p., 123 volts	do.	5	19.5	25 per cent below and 25 per cent above.	20 per cent below and 25 per cent above.	70
Regular.						
16 c.-p., 80 volts	Oval	16	56	25 per cent above and 25 per cent below.	17 per cent above and 17 per cent below.	450
32 c.-p., 80 volts	do.	32	115	do.	do.	300
32 c.-p., 110 volts	do.	32	115	do.	do.	300
32 c.-p., 123 volts	do.	32	115	do.	do.	300
Diving.						
100 c.-p., 80 volts	Double loop.	100	250	30 per cent above and 30 per cent below.	25 per cent above and 25 per cent below.	......
100 c.-p., 110 volts	do.	100	250	do.	do.	......
100 c.-p., 123 volts	do.	100	250	do.	do.	......

Tests.

Lamps are tested for the purpose of determining the initial voltage, the total watts expended at the rated candle-power, the physical characteristics of the lamps and for life. The requirements as to electrical qualifications are given in the table on page 589.

Physical tests require an examination of the bases, filaments and the vacuum; loose bases, spotted or discolored filaments or a poor vacuum being sufficient to reject them.

From each quantity of lamps submitted for test, 10 per cent, known as the test quantity, shall be selected at random for test for the purpose of determining the mechanical and physical characteristics of the lamp, the individual limits of candle-power and watts per lamp and the life and candle-power.

If 10 per cent of the test quantity show any physical defects, the entire lot may be rejected without further test.

When tested at rated voltage, the test lamps shall not exceed the limits given in the schedule. If 10 per cent of the test lamps is found to fall beyond the limits stated, the entire lot may be rejected without further test.

Unit of Candle-Power.—The unit of candle-power is the candle as determined by the Bureau of Standards at Washington, D. C.

Photometric Measure.—The basis of comparison of all lamps is the same spherical candle-power. The nominal candle-power is the mean horizontal candle-power of lamps having a mean spherical candle-power value of 82.5 per cent of the mean horizontal candle-power. This is the standard value for filaments of the oval anchored type, other type filaments having a different percentage value.

Life and Candle-Power Maintenance.—Life tests are made as follows: From each accepted package of lamps two sample lamps are selected which approximate most closely to the average of the *test quantity.* One of the two lamps thus selected will be subjected to a life test and designated as the *life test lamp,* the second or duplicate lamp being reserved to replace this *test lamp* in case of accidental breakage or damage during the life test. *The test lamps* are operated for candle-power performance at constant poten-

tial, average variations of voltage not to exceed one-fourth of 1 per cent, either side. The voltage for each lamp shall be that corresponding to an initial specific consumption of 3.76 watts per mean spherical candle, or, if tested upon a different basis, the results shall be corrected to a basis of 3.76 watts per mean spherical candle.

Readings for candle-power and wattage are taken during life at the marked voltage of the lamps at approximately 50 hours, and at least every 100 hours afterwards until the candle-power shall have fallen 20 per cent below the initial candle-power, or until the lamp breaks, if within that period. The number of hours the lamp burns until the candle-power has decreased to 80 per cent of its initial value, or until the lamp breaks, is known as the useful or effective life.

The average candle-power of lamps during life shall not be less than 91 per cent of their initial candle-power. In computing the results of test of a lot of lamps the average candle-power during life shall be taken as the arithmetical mean of the values for the individual lamps of the lot tested.

Accurate recording voltmeter records are obtained during the test on lamps to show the average variation on the circuit.

When so tested the lamps shall average at least the values for useful life given in the table.

Illumination.

Illumination is the amount of light falling upon some unit of area, as a square foot, of the surface to be lighted and is independent of the nature of the surface, and the light may be either reflected, absorbed or transmitted. The illumination depends upon (1) the quantity of light from the source and (2) the distance between the body illuminated and the source. The unit of illumination generally accepted is the *candle foot*, being that amount of light falling upon a body at a distance of one foot from a standard candle. The intensity or amount of light per unit area also varies inversely as the square of the distance from the source of light. The question of the kind and location of incandescent lamps for ordinary ship's illumination is one that presents few difficulties, but one that creates at times considerable criticism. One candle

foot is a convenient illumination for reading. For the ordinary heights on shipboard, one 16-candle-power lamp will illuminate well about 50 square feet of surface. As a matter of efficiency, pure and simple, that is to get the greatest amount of light from a given power, it would appear that all lamps installed should have naked, clear glass bulbs; but other questions than efficiency, especially on shipboard arise, such as personal taste, structural details and the effect on the eye in reading, writing or working.

For lighting in cabins and state-rooms, it is usual to use frosted globes, these being necessary for comfort and appearance even though some of them absorb even as much as 60 per cent of the light emitted. This loss of light seems a great waste, but not as much perhaps, as would seem on first glance. The filament in a frosted globe is invisible and the whole bulb looks as though it were the source of light, and the luminous area being thus enlarged, there is less contrast between the source of light and the objects lighted. In reality, the frosted globe is a better dispenser of light than the clear globe, each little particle of the rough glass acting as a prism, refracting the rays in all directions. A room with a naked gas flame appears poorly lighted compared to the same flame surrounded by a globe although the light emitted is certainly less in the latter case. It is often a question whether for reading or desk work a clear bulb high up or a frosted one low down will give the best results; the amount of light received being not far from the same in both cases; the clear one losing in intensity due to its distance away. It seems perfectly proper not to use clear globes when they come within direct and constant range of the eye, as the pupil of the eye will involuntarily contract at the dazzling light, and it is doubtful if more rays actually enter the eye than in case of the frosted globe.

Overhead lighting seems to be best adapted for ships' use for standing lights in open spaces where men are not berthed and side lighting where they are. In store-rooms and passageways, it is usual to place the lights where they are least in the way of movables, general illumination only being required.

Simply as a matter of illumination and uniform distribution of light, a small number of low candle-power lamps is better than one

lamp of the combined candle-power, thus four 16-candle-power lamps would give a better general effect than two 32's, although no more power is absorbed.

The question of color of sides or ceiling of a room has considerable to do with the lighting effect. Dull and dark surfaces absorb as much as 80 per cent of the light incident on them, while clean, white surfaces will reflect that much, adding to the general effect. With fairly white walls, a rule which allows two watts for every square foot of floor area, is one that would give more than ample illumination.

Tantalum and Tungsten Filaments.

The conductivity of metals is very much higher than that of carbon and several varieties of metal filaments have been used in lamps of recent manufacture. Owing to the high conductivity, the use of a long wire of small diameter is necessary and a filament of tantalum presents the unusual appearance shown in Fig. 146. With ductile metals as tantalum such a filament is comparatively easy to make, but with non-ductile metals like tungsten, the method is not so simple.

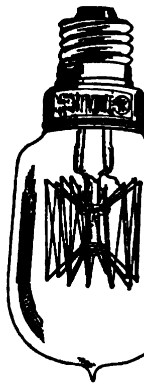


FIG. 146. The Tantalum Filament Incandescent Lamp.

To make a tungsten filament, a carbon filament is first made which is electroplated with metallic tungsten. This is then *flashed* in an atmosphere of hydrogen at very high temperature which results in the absorption of the tungsten by the filament and the production of carbide of tungsten. The carbon is removed by heating the filament to a high temperature while it is surrounded with tungsten oxide. The carbon oxidizes and passes off leaving the metallic tungsten filament.

The Nernst Lamp.

Although the Nernst lamp has not been used in the naval service, it is of interest on account of the principles involved in its construction and of the high efficiencies obtained.

This lamp differs from the ordinary incandescent lamp in that it is not enclosed in a vacuum, and instead of the filament being made of carbon, it is made of some highly refractory oxides "rare earths," such as zirconia, thoria or yttria, made in the form of little rods and mounted on platinum wires by means of a paste of the refractory oxides. The lamp is operated in air and is only protected by the very high melting point of the filament. This filament is a non-conductor when cold but becomes a conductor when heated and its resistance decreases as the temperature increases. This is corrected by a steadying resistance in series with the filament, and including this resistance, the efficiency varies from .8 to 1.8 watts per candle-power. The steadying resistance is enclosed in a glass tube from which the air has been exhausted to protect the wire from oxidation.

In order to make it conducting, the temperature is raised by what is called a *heating resistance* in shunt with the filament and close to it. The heater consists of one or more clay tubes wound with high resistance and covered by fire-clay. When the filament commences to conduct, a cutout disconnects the heater.

This lamp finds its greatest application for outside illumination, though with frosted globes it is very satisfying for large interior spaces.

CHAPTER XIX.

ARC LIGHTS.

The arc light is the oldest form of electric light known. Until recently it found no practical use for lighting on shipboard but now it is used in large spaces for general illumination as in the engine-rooms of large modern vessels. The application of the arc light to the focus of a reflecting minor, spherical or parabolic, in an enclosure to give a beam of reflected light gives the search-light.

General Principles.—If two carbon points, forming part of a closed circuit in which a current is flowing, be separated a short distance and the current is strong enough, a spark will jump from one to the other. If the current continues steady and strong enough, a series of sparks will continue to jump from one to the other and if the distance between them is not too great, a flame will soon form, and this flame gives out light and heat. The explanation is as follows: The current passing from one carbon to the other is suddenly arrested when the carbons are separated, or more properly speaking, the current meets with a greater resistance, that of the air between the points, and the first spark is due to the high E. M. F. of the momentarily self-induced current. The current continues to flow through this high resistance, the result of which in a short time is to heat it; that is the air gap, to such a degree that it becomes incandescent.

The incandescent flame produced between the points of the carbons has a violet appearance, and from the fact that the original source of E. M. F. was a voltaic battery, it is commonly called the "voltaic arc." The word arc is a corruption of "arch," which was originally used to designate the shape of the flame.

Production of the Arc.—The operation of producing an arc by first bringing the carbons in contact and then separating them is commonly known as "striking the arc." The reason for this pre-

liminary contact is that it would require a much greater E. M. F. in the circuit to start an arc across even the thinnest filament of air between the carbons. When the carbons first touch and current flows between them, the junction gets very hot owing to the resistance of the imperfect contact and when separated, the heat volatilizes some of the carbon and lowers the resistance sufficiently to allow the current to continue to flow.

Electrodes.—The choice of electrodes used with the arc is practically limited to carbon in some form or other. The intensity of light depends on the temperature at which volatilization takes place, and most metals have a low temperature of volatilization compared with carbon, and their temperatures of incandescence are very near their melting points. Carbon cannot be melted into a liquid state, but passes direct from the solid into the gaseous state, or volatilizes, only at a very high temperature.

Form and Temperature of Arc.—The result of the great heat formed in the arc is to heat the carbon the current leaves, the positive carbon, and this heat produces a carbon vapor that is projected across to the negative carbon. The vapor helps to form a conductor for the current and becomes incandescent. This incandescent vapor is not the chief source of light, for solids are better radiators than gases, and the carbon tips are much hotter than the vapor. The temperature is so high that the positive carbon actually boils, and this glowing portion is the chief source of light.

The vaporization goes on most intensely in the center of the positive carbon, lessening as the distance is increased from the center, and this burns a hollow-shaped cavity in the positive carbon forming what is known as the **crater.** This crater is the source of most of the heat and light, very little coming from the arc, and scarcely any from the negative carbon.

As the carbon vapor is projected across to the negative carbon, part of it condenses and builds up this carbon to a conical point, though the carbon as a whole burns away.

The positive carbon is supposed to be at a temperature between 5000° C. and 6000° C., while the negative carbon is probably between 2000° C. and 3000° C. On account of this difference in temperature, the positive carbon wastes away faster than the nega-

tive one, and, as it has been said, part of the vapor from the positive carbon condenses on the negative one.

The above considerations are only true for arc lights produced by continuous currents, but if the arc is produced by alternating currents, the electrodes are acted upon alike in every particular, for one is positive at one instant and negative at the next; and they will be consumed at equal rates and will assume the same shape in their tips.

In continuous currents, the rate of consumption of the positive carbon is about twice as great as that of the negative one, and the rate of consumption depends on whether the arc is enclosed or not.

Back E. M. F.—In addition to the ohmic resistance of the arc it has the peculiarity of exerting a *back* or *counter E. M. F.* This back E. M. F. opposes the applied E. M. F. of the circuit producing the arc and seems to range between 35 and 40 volts, many experiments seeming to show that 39 volts is about the average value of this E. M. F. This shows that to operate successfully an arc light, the impressed voltage must be of a value sufficiently high to overcome the back E. M. F. as well as to overcome the ohmic resistance of the arc. This latter varies almost directly with the distance between the carbons. In the arc, it should be remembered that the *voltage* varies directly as the *length of arc* and the *current inversely.* This means that the farther the carbons are apart, the greater the difference of potential between them, and the less the current that flows between them, and to this extent Ohm's law is not applicable.

The explanation of the back E. M. F. is given by Professor S. P. Thompson as follows: In the transformation of the carbon from the solid to the gaseous state, a certain amount of latent heat is absorbed by the vapor without raising its temperature. As this vapor condenses on the negative carbon, this latent heat is released and in doing this it develops, in a reverse sense, the electrical energy which produced the original transformation of the vapor.

Resistance of the Arc.—The true resistance of the arc depends on the *ohmic resistance* of the space separating the carbons, and the resistance of the back E. M. F. which is sometimes called the *apparent resistance.* The ohmic resistance depends on the distance

separating the carbons and may vary between $\frac{1}{10}$ and 10 ohms, while the apparent resistance is a fixed quantity. In an open-type arc taking 10 amperes with a length of arc giving $\frac{1}{2}$ ohm resistance, the E. M. F. necessary to overcome this resistance would be 5 volts, which, added to the 39 volts of the apparent resistance, would make 44 volts necessary to operate such an arc. Ordinary open arc lights take from 45 to 55 volts and enclosed arcs from 60 to 160 volts.

An arc lamp has one length of arc with which it will act best, and a lengthening of it will produce *flaring* of the flame, and the flame will leave the tips and burn around the edges, while a shortening will produce violent hissing and sputtering. With the proper length of arc the flame will burn quietly and smoothly.

Carbons.—The carbons used for arc lights are generally made from graphite, a powdered form of carbon, deposited on the inside of the retorts used in the manufacture of coal gas. It is powdered, mixed with a syrup to make the particles adhere firmly and then molded in the proper form and baked hard. They are made with an inner core of softer carbon, having less resistance than the outside, thereby tending to hold the current near the center of the carbon, facilitating the first formation of the crater in the center and keeping it there. The finished carbons are given a thin electroplated coating of copper which increases the original conductivity of the carbon, besides adding to its duration from 30 to 40 per cent.

The size of the carbons depends on the current used, one for 50 amperes, as a search-light, requiring a diameter about $\frac{22}{32}$ to $\frac{24}{32}$ of an inch. On account of the boiling of the positive carbon, it wears away about twice as fast as the negative one, this last losing by the incandescent particles of carbon being thrown against it, tearing and wearing it away. The negative carbon is smaller in diameter than the positive as it does not lose as much as the positive. The lengths depend on the time they are required to burn, one 12 inches long will burn from 7 to 12 hours in an open arc, but in a closed arc, a pair of ordinary carbons will sometimes last 150 hours.

Regulation of the Arc.—While the arc lasts, the carbons are quickly consumed, and the air gap widens until a point is reached when the resistance is so great that the current will no longer main-

tain the arc and the flame or arc is extinguished. To relight, the carbons must be touched again and at the instant the current flows, must be separated the proper distance.

The lamp of an arc light must then automatically (1) *cause the regular and gradual approach of the carbons towards one another, or one toward the other;* (2) *produce the initial spark by bringing the carbons in contact and separating them the proper distance at the instant current is established;* (3) *hold the carbons at a certain distance, called the length of arc, previously determined for the current used and the intensity of light required.*

The lamp of a search-light must satisfy the above three conditions and in addition must (4) *provide means by which the arc is kept continually in the focus of the mirror,* as the positive carbon wears away faster than the negative one. All four of the above conditions are satisfied in the construction of the search-light lamp, partly by mechanical and partly by electromechanical means.

Principles of Regulation of Search-Light Arcs.

Arc lights used as search-lights on board ship require on an average of 45 volts between the carbons to produce and maintain a steady arc, about 39 volts being absorbed in doing the work of vaporizing the carbon. As search-lights are worked in parallel with incandescent lamps, requiring a higher voltage, a dead resistance must be inserted in each search-light circuit to cut the voltage down to the required difference of potential between the carbons. As the light given out depends on the number of watts absorbed, both the voltage and amperage may be varied, the former, however, within very narrow limits.

We have thus two electrical factors to vary, volts and amperes, the varying factors being the length of arc and the resistance in the circuit. These four are intimately connected, a variation in either the length of arc or of the resistance producing changes either in the difference of potential or current or in both.

For a certain maximum length of arc, the least difference of potential between the carbons is fixed, and with this length of arc the current may be varied by changing the dead resistance. If from any cause the length of arc becomes smaller the difference of

potential decreases, but the current increases without any change in the dead resistance. So, if a certain difference of potential is decided on the current may be carried by a change in the dead resistance.

If a certain current is decided on, it can be obtained by changing the length of arc, or if that is fixed, by changing the resistance, or both may be changed.

If both the differences of potential and current are fixed, the former can be regulated by giving the maximum length of arc, and then the current can be obtained by varying the dead resistance. This last condition is the one generally adopted in actual practice, the difference of potential or maximum length of arc, being adjusted by the tension of a spring acting against the mechanism which feeds the carbons together, and this then being a fixed quantity, the desired current is obtained by one certain fixed resistance. This presupposes that the lamp is perfectly automatic, that is, it keeps the arc constantly at the same length, and if such were the case, it would require no further attention.

However, no lamp is perfectly automatic, and any consequent change in the arc must be corrected, while the lamp is working, by varying the resistance.

In most lamps, there is no provision made for feeding the carbons apart if by any chance they get too close, and while they are naturally wasting away, the current must be controlled by the resistance. If the carbons get too far apart, the mechanism then acts to feed them together.

Action of the Dead Resistance.

Fig. 147 shows the action of the dead resistance in the circuit in causing the necessary drop in potential, R being the resistance introduced in series with the main current and R' representing the resistance of the arc.

If the carbons are far apart, so that R' is practically infinite, a voltmeter connected as shown at V would indicate the full voltage of the circuit and one connected to the terminals of the resistance R would not indicate, the circuit through it not being complete.

If the arc is once struck so that the resistance of the main circuit

is very much lowered, and a large current flows through R', V will then indicate the difference of potential at the carbons, or the fall of potential through R', and V' will indicate the fall of potential through R. Knowing the current desired and the drop through R' necessary, R may be calculated to give the proper drop through it. When the current is flowing the sum of the two readings of V and V' will be the same as that indicated on V when no current was flowing through R'.

The figure shows a typical search-light circuit, ammeter A being inserted in the circuit, V' connected as shown, V being omitted, as the reading obtained by that can be obtained on the switchboard voltmeter, as it is in fact the full voltage of the generators.

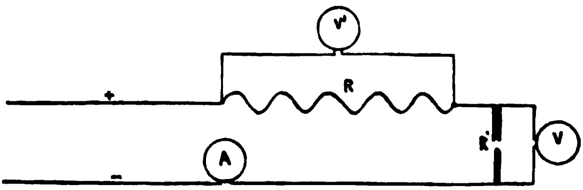


FIG. 147.—Action of Dead Resistance.

The resistance R should always be of such a value as to cause steady working and of sufficient reserve to prevent a short circuit in the mains. It should be sufficiently large to withstand heavy currents without undue heating, with provision for ventilation.

Calculation of R.—Suppose a search-light was to be worked at 50 volts, and of sufficient size to carry 50 amperes, then the resistance of the arc would be, $R = \frac{E}{C}$ or $R = \frac{50}{50} = 1$ ohm. If the full voltage was 80, the fall through the resistance R' must be $80 - 50 = 30$ volts. The current through R' being 50 amperes, by Ohm's law $E = CR$ or $R = \frac{E}{C}$, $R = \frac{30}{50} = \frac{3}{5}$ ohms.

The total resistance then in circuit is $1 + \frac{3}{5}$ ohms or $C = \frac{E}{R}$ where E and R represents total E. M. F. and total R,

or $$C = \frac{80}{1 + \frac{3}{5}} = 50 \text{ amperes.}$$

This is also arrived at as follows:

CD is the fall through the arc and DE is the resistance of arc, AB is total fall and x is the resistance to be inserted, then by similar triangles (Fig. 148),

$$\frac{AB}{CD}=\frac{1+x}{1} \text{ or } \frac{80}{50}=1+x \text{ or } x=\frac{3}{5}.$$

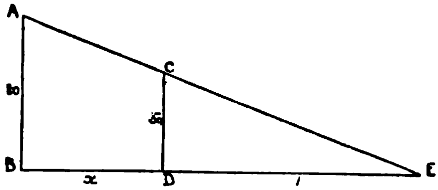


FIG. 148.

Horizontal Lamp.

Having now shown what a good automatic lamp should be capable of doing as explained under regulation of the arc, a description of one horizontal lamp now used in the service will be given.

Fig. 149 is intended to show the general working mechanism of the lamp and the action of the current is making it automatic. Current is brought to the lamp from slide contacts in the projector, these contacts receiving current from the mains through a switch in the pedestal of the projector. When the lamp is placed in position in the barrel of the projector, the terminals of the lamp press against the slide contacts, making sliding connection, to enable the lamp to be moved in and out from the mirror for the purpose of focusing. The lamp terminals are shown at *a,* being one on each side, the further one, positive, not showing in the figure. From the positive terminal, the current flows around an electromagnet *b* in series with the main current; the end of the magnetizing coil being secured at *c,* on the iron piece *d,* which in turn is secured to the core of the electromagnet. The iron piece *d* is in contact with the metal framework of the lamp, the sides of the frame being shown removed. Any part or point of the frame may be considered as the positive terminal of the arc, as it is in direct metallic connection with the main current.

From the piece *d* in contact with the frame, current finds its way through the end pieces of the framework, through the screw spindle *e*, through the two upright supports of the positive carbon *f*, through the positive to the negative carbon, down the two uprights *g*, through the connecting piece *h* to *j* and down the latter to the negative terminal of the lamp. The uprights *g* are insulated from the rest of the framework, this allowing all the framework to be of

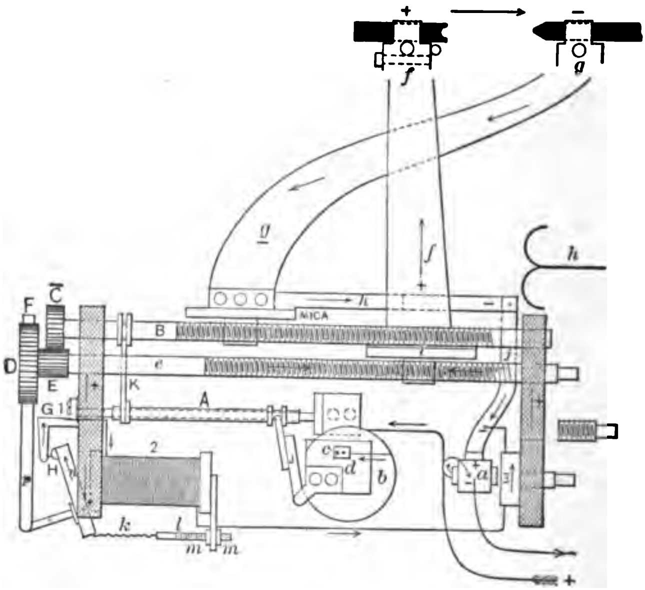


FIG. 149.—Horizontal Lamp.

the same potential. Current also finds its way from the side at *i* to the positive uprights, the uprights *f* being provided with flanges sliding in slots in the side of the frame.

For the automatic working of the lamp, there is a shunt circuit taken from the main current, this shunt circuit controlling the automatic mechanism. The positive terminal of this shunt circuit may be considered as any part of the framework, such as the point where the armature *n* of the electromagnet 2 is pivoted to the frame. The shunt current from here flows through the armature

n, through the flat copper spring *H*, which acts as a contact breaker, through the contact point on the bracket *G*, through the bracket *G* which is insulated from the frame, through and around the electromagnet 2, to the automatic switch 3 and to a point on *j*, acting as the negative terminal.

The two uprights *f* are connected at the bottom by a cross-piece to which is secured a lug with a thread cut in it and through which screws the spindle *e*. A rotary motion given to *e* causes the uprights carrying the positive carbon to move along the spindle. Motion is given to the uprights *g* carrying the negative carbon in a similar manner by the rotation of the spindle *B*. This spindle also has a lengthwise motion through its bearings in the ends of the frame, allowing the uprights to be moved a short distance without a rotary motion of *B*. This provision is made in order to strike the arc, and to do this one carbon must move independently of the other, thus necessitating a flexible connection. In striking the arc, the two uprights *g* move and they are connected to the upright *j*, a rigid solid conductor, by a conductor of flexible copper ribbon, of a shape shown on the right at *h*, so when *g* is moved to the right or left, the copper ribbon bends back or unrolls on itself.

The spindles *B* and *e* are connected to each other through the gear wheels *C* and *E*, and if the spindle *e* is turned the carbons are either brought closer together or further apart, the threads being right-handed and of equal pitch. To make provision for the positive carbon wasting away faster than the negative one and in order to keep the arc always in the same place, the gear wheel *C* is twice the size of *E*, so a motion given to *E* will only cause half the motion in *C*, or in other words, any rotary motion given to the spindle *e* will cause the positive carbon to either approach or recede from the negative one at a rate twice as great as the negative carbon moves.

The uprights holding the carbons have clamp screws to hold them, and the positive one is fitted with tangent screws, by which the end of the positive carbon may be slightly raised or lowered, or turned to the right or the left so as to accurately center the arc, and make the carbons burn evenly.

The movement of the spindle *B* in striking the arc is controlled by the electromagnet *b*, through the armature *J*, sleeve spindle *A*

and rod K. J is the armature of the series magnet, pivoted as shown, and when attracted towards d, communicates its motion through a connecting piece with an end clutch to A which slides on a rod, carrying K which has a forked arm, engaging the clutch on B. When J moves to the right the negative carbon moves the same way, the positive one remaining stationary. The amount of motion of A to the left is determined by a screw stop-pin through the left-hand end piece and to the right by J bringing up against the armature d, so the initial separation of the carbons is limited.

n is the armature of the shunt magnet 2, and when this magnet is energized, the armature is attracted, pulling the copper spring contact away from the contact pin, breaking the circuit. The piece o pivoted to p is rigidly connected to n, and when n is attracted to the magnet, p is pushed up, turning an arm, not shown, carrying a pawl F which engages the teeth on D connected to the spindle e. When the circuit is broken, n is pulled back in place by the spiral spring k, hooked to a small screw spindle l, and in doing so, p is pulled down, the pawl F revolving the wheel D, which sets in motion the spindles e and B, feeding the carbons together. As soon as the contact spring H comes in contact with the point, the circuit is re-established and the same motions repeated. This make and break gives an alternating movement to the feeding pawl as long as current flows through the shunt magnet. There is a stop on the left not shown which regulates how many teeth the pawl F engages, so the feeding may be fast or slow.

The tension of the spring k regulates the difference of potential at which the carbons will feed, for the greater the tension, the stronger must be the current; or, in other words, the higher the voltage necessary to attract the armature n. The tension of the spring k is regulated by two stop nuts m, m.

Suppose the tension on the spring k has been regulated to give the difference of potential at which it is required the carbons will feed and the carbons are just touching. The main switch at the base of the projector is turned, and immediately the whole current flows through the series magnet, the circuit being completed through the carbons. At this instant, the series magnet b is energized and the armature J attracted, and as has been explained the negative

carbon is drawn away from the positive, striking the arc. The resistance of the arc at this time is such that all the current flows through the carbons, there not being enough difference of potential between the carbons to cause enough current to flow through the shunt magnet to overcome the tension of the spring *k*. The carbons gradually burn away, and as they do, the resistance of the arc increases, the difference of potential increases to the amount for which the spring *k* was set and current flows through the shunt magnet. This starts the feeding mechanism as explained and the carbons are fed together again, the difference of potential gradually falling until the spring overcomes the shunt current and the feeding stops. This arrangement constitutes the automatic working of the lamp. If by any chance the carbons get too close, there is no provision made for feeding them apart and they must burn away.

If it is required to work the lamp by hand, the automatic switch 3 is turned by a wrench on the right-hand end, and this simply breaks the shunt circuit, when the carbons can be fed by a wrench on the end of the spindle *e*.

In order that the arc may be accurately put in the focus of the mirror, there is a screw spindle, projecting through the projector which screws into a screw thread cut in the face of the lamp frame, and turning this moves the lamp towards or from the mirror.

In horizontal lamps, there is a tendency for the flame to ascend, due to the heated air, and to prevent this, and to center the arc and make it burn evenly there is a ring of magnetic material surrounding the arc. This creates a uniform magnetic field around the arc which centers it and makes it burn evenly.

The Balancer.

The introduction of a dead resistance in the leads of a search-light arc to reduce the generator voltage to that required to sustain the arc results in the expenditure of energy that does not appear as light. This loss is not so great when the arcs take small current and the search-lights are few in number, but as both the size and number increase the waste energy becomes a matter of great importance.

In the example given, the energy consumed is $80 \times 50 = 4000$

watts, of which the arc only consumes $50 \times 50 = 2500$ watts, a waste of 37.5 per cent, and numerically 2 horsepower. This loss takes place in the dead resistance and is dissipated in the form of heat, the C^2R loss being $50 \times 50 \times \frac{3}{5} = 1500$ watts.

To reduce this loss, the machine known as the **balancer** has been devised. This is similar in appearance to a motor generator, with the field of the motor in series with the armature while the generator field is differential wound. Its action will be understood by reference to Fig. 150, which shows the method of connection to the leads.

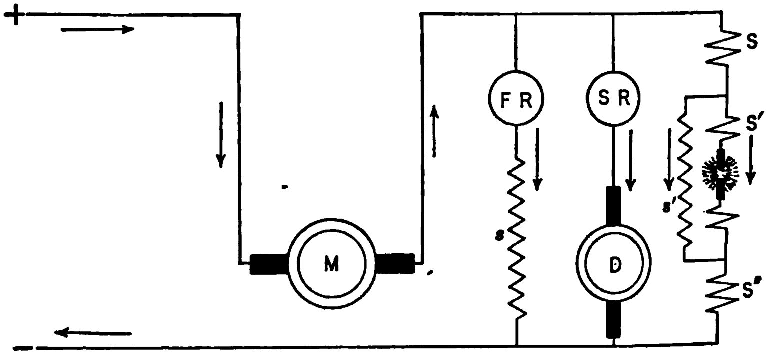


FIG. 150.—Elementary Connections of the Balancer.

The arc leads are marked + and — (Fig. 150), with the motor *M* connected in the line, and *S* is its series field. *D* is the generator connected directly across the line with its shunt field *s*, *FR*, field rheostat, and *SR* a starting rheostat. *S''* is the series field of *D* wound differentially with respect to *s*. *S'* is the series winding and *s'* the shunt winding of the lamp-regulating mechanism.

When the carbons are separated and the main switch closed, current flows as indicated by the arrows. Under this condition, *D* acts as a motor under the action of the constant field due to *s* and drives *M*. The current through *M* is small, as the carbons are separated, and the resistance of *s'* is high. From the fact that the current is small, the field of *M* through *S* is but feebly energized, consequently the counter E. M. F. of *M* is low, and the fall of potential through *M* is also low, being equal to $c_a r_a$ of *M*. The

terminals of the lamp shunt s' receive practically the full voltage of the line and the shunt current acts to feed the carbons together.

As soon as the carbons touch and current flows through them, the entire condition is changed. The field of M, S, is now fully energized and M now acts as the prime mover, driving the armature of D. This current flowing through S'' reduces the field of D, as the fields are oppositely wound, and reduces the counter E. M. F. D acts as a generator and the current through it is reversed. The counter E. M. F. of M increases as the field is strengthened, and the excess of line voltage over that required for the maintenance of the arc is represented by the counter E. M. F. developed. The current through M depends on the difference of potential at the carbons, on the counter E. M. F. and on the armature resistance, and it may be lower than that required to actuate the arc, in which case the deficiency is made up by that generated by D. This represents the saving effected by this device as the current is not drawn from the main generator.

As the carbons burn apart and the resistance increases, the field current of M decreases and the armature speeds up. This decrease of current decreases the series effect of D, and both causes, the increase of speed and field, results in an increase of the difference of potential at the lamp shunt terminals and the carbons are fed together.

If the carbons get too close together the increased current causes M to slow down, and also decreases the field of D which causes it to lower the voltage at the carbon terminals.

Search-Light Projectors.

The projector carrying the lamp consists of a fixed pedestal surmounted by a turntable carrying the projector proper. The pedestal is arranged so it can be securely bolted to the deck or platform and fitted to contain the electrical connections.

The turntable is so designed that it can be revolved in a horizontal flame freely and indefinitely in either direction or clamped rigid if desired.

The drum is trunnioned on two arms bolted to the turntable and has free movement in a vertical plane of 70° above and 30° below

the horizontal. The drum can be rotated on its trunnions by hand or clamped rigidly in any position, and while clamped may be given a slow movement in altitude by turning a small handle in the axis of the pedestal. The drum is fitted with peep sights for observing the arc in two planes, in the side by a colored piece of glass and in the top by reflecting prisms. The drum is designed to contain a parabolic mirror.

The mirror is of the best quality of glass and should be free from all flaws and holes, with its surface ground to exact dimensions. The back is silvered in such a way as to be unaffected by heat. The glass is mounted in a separate metal frame lined with a non-conducting material to allow for expansion due to heat, and to prevent injury from concussion.

The front of the drum is provided with a glass door composed of strips of clear plate glass.

The lamps produce the best results when taking current as follows:

13-inch	18 to 20	amperes.
18-inch	30 " 35	"
24-inch	40 " 50	"
30-inch	70 " 80	"
60-inch	150 " 200	"

The 18-inch projector is supposed to project a beam of light of such intensity as to render plainly discernible, on a clear dark night, a light-colored object 10 $\times$ 20 feet in size, at a distance of not less than 4000 yards, the 24-inch projector at a distance of not less than 5000 yards and the 30-inch projector at a distance of not less than 6000 yards.

For the care and management of search-lights see chap. XI, vol. II.

Enclosed Arc Lamps.

Enclosed arc lamps are now being used on shipboard to some extent, especially in engine-rooms, where a large area requires general illumination. These lamps differ from ordinary arc lights in that the arc is surrounded by a small glass globe which fits the carbons so closely that the air inside the globe can only slowly change. One effect of this is to reduce the rate of combustion of

the carbons which also lessens the work of the feeding mechanism. The enclosed air becomes a source of light, so that the whole globe seems to glow and increases the apparent amount of light.

Enclosed arc lights require a higher voltage than open arcs, 60 volts being about the minimum, and take from 2 to 10 amperes.

Lamps are furnished to operate on voltage of 80, 110 or 125 volts with a current not exceeding 4.5 amperes. The arc is enclosed by an inner opal globe, which is surrounded by a clear globe protected by a composition guard. The guard and outer globe are removed together and so held by supporting chains that the inner globe may be removed to renew the carbons.

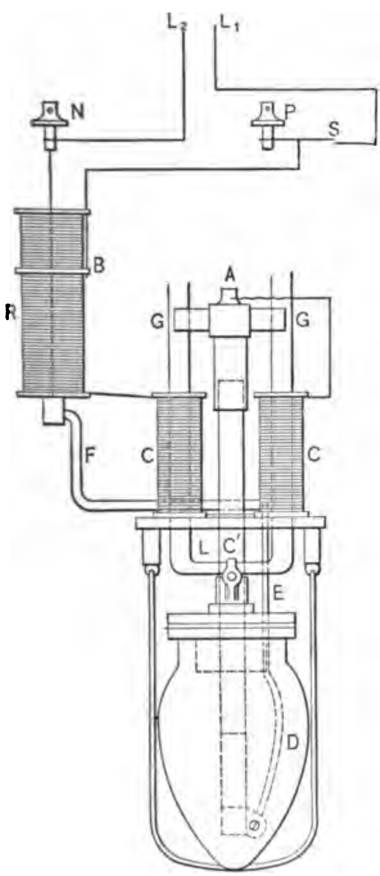


FIG. 151.—Form 12 Arc Lamp. General Electric Company.

Carbons are ½ inch in diameter and have a life of 120 hours without trimming.

Each lamp contains the proper resistance for reducing the line voltage to that required for the best regulation of the arc, an average of about 85 volts.

A commercial form of lamp that meets the required specifications is made by the General Electric Company and is shown diagrammatically in Fig. 151. L_1 and L_2 are the line leads, and are wired in multiple from the lighting mains. L_1 is connected to the positive terminal of the lamp P, through the switch S, on top of the lamp. From the positive terminal, the circuit leads to the edgewise wound rheostat R, through the sliding contact B, which can

be moved up or down along the rheostat. This throws more or less of the resistance of R into circuit and acts as the dead resistance previously described. From the rheostat the circuit leads to the electromagnets *C, C,* and thence to the terminal *A,* which is a part of the support holding the upper, positive, carbon of the lamp. Current flows from the positive carbon to the lower, negative, carbon, then to the curved conductor *D,* vertical conductor *E* and curved conductor *F,* up through the center of the rheostat to the negative terminal *N* of the lamp and thence to the line lead L_2.

The positive carbon is held by a clutch *C′* through a bell crank arm and acts to grip the carbon and raise it when the support is raised, but on lowering when the clutch comes against the top of the inner globe support, the clutch opens and allows the carbon to fall until it brings up against the negative carbon, so at all times the lamp is ready for operation.

Before current is switched on the carbons touch, but as soon as the electromagnets are energized, the plunger *L* is sucked into the core of the solenoid, and at the same time the clutch grips the positive carbon, raising it, and thus strikes the arc. As the carbons burn away and the length of arc increases, the resistance increases, consequently the current through the arc lessens and the plunger is not held so strongly in the magnets and it drops, until the increased current is sufficient to hold it at the proper distance for the voltage across the arc.

The working mechanism of the lamp is protected from dust and dirt by a bronze sheet-copper casing, and there should be no occasion to remove this as the rheostat is properly adjusted and should not be changed.

Candle-Power of Arc Lights.

The candle-power of arc lights is rather a deceptive means of determining how much light an arc is producing. For instance, a so-called 2000-candle-power arc light does not give more than 1400 candle-power in the direction of greatest intensity. The same considerations hold for arc lights as for incandescent lights regarding their mean spherical candle-power; that is, it is the average candle-power on the surface of a sphere with the light at the center.

However, there is a great difference between the horizontal candle-power and the maximum candle-power, the latter being found, in vertical arcs with the + carbon uppermost on a line making an angle of 45° with the horizontal. This is due, of course, to the reflection from the crater on the positive carbon, this acting as a reflector and throwing the light down, and besides the incandescence of the positive carbon being the principal source of light.

An empirical rule for finding the mean spherical candle-power is to add one-half the mean horizontal candle-power and one-quarter of the maximum candle-power. From the direction of the maximum ray, it is very evident that for a search-light to give out the most light, the carbons should be so placed that the rays of greatest intensity shall be the ones that should be reflected from the mirror. In other words, the carbons should be horizontal, with the positive carbon farthest from and pointed towards the mirror, and this is the case with all present designs of search-lights.

The practical method of determining the candle-power is to find the power in watts absorbed to produce it. The mean spherical candle-power can be determined by using the arc in connection with the photometer, finding both the horizontal and maximum candle-power; and at the same time by properly connecting a voltmeter and ammeter, the number of watts absorbed can be found. When the arc is used as a search-light, and the product of the volts and amperes show a value equal to that found when the candle-power was being tested then the arc is producing its rated candle-power. Different shaped carbons or different adjustments may vary the intensity or direction of the maximum ray, but with the same number of watts, the *mean* candle-power remains practically the same.

The maximum candle-power can be determined by connecting a voltmeter and ammeter in circuit, and varying these quantities until their product is a maximum. The range of voltage is practically limited to a few volts, the greatest current consistent with steadiness of arc, proper length of arc and the carrying capacity of the carbons may be found. When a light is being used under the conditions determined for maximum candle-power, or the product of the two variables is the same, then it may be certain that the arc is giving its maximum mean spherical candle-power.

Flaming Arc Lights.

In the ordinary carbon arc light, most of the light is produced by the incandescence of the carbon terminals, and improvements have been made in making the arc itself luminous. The addition of materials such as calcium and strontium to the carbons results in the production of very highly luminous and efficient arcs. The carbons produce a vapor path by which the light-producing materials are conveyed from one terminal to the other. From the appearance of these arcs, they are called "flaming arc" lamps. Their efficiency is about ten times as great as that of the carbon arc. On account of the fumes given off by these arcs they can only be used for outdoor lighting or in places where there is good ventilation.

Mercury Vapor Lamps.

A mercury vapor lamp consists simply of a highly exhausted glass tube containing mercury, and fitted with an electrode at each end. The tube contains some vapor of mercury at all times. Ordinarily the tube hangs in a slanting position so that the mercury collects in a reservoir at its lowest end around the negative electrode and forms part of it. To start the lamp, it is raised, either by hand or automatically, to a horizontal position, when the mercury runs out of the reservoir and into and along the tube to the positive electrode. This establishes a current, and upon breaking the stream of mercury by allowing the tube to fall into its normal slanting position an arc jumps across the gap, and the volatilized mercury conducts the current, being heated to incandescence thereby and giving out light. Mercury is continually vaporized, is condensed upon the cooler portions of the tube and trickles back to the reservoir.

A peculiarity of electrodes immersed in mercury vapor consists in what is known as the "negative electrode resistance," and the effect of it is that an arc cannot be struck in mercury vapor except upon the application of a momentary high E. M. F., about 5000 volts. This "negative electrode resistance" is not resistance in the ordinary electrical sense of the word, since resistance in a direct current allows current to flow exactly in proportion to the E. M. F. applied, however high the resistance may be, while the property in

question absolutely obstructs all current until it is overcome by the requisite E. M. F. when it practically disappears and the current can be maintained by ordinary line voltages. It is somewhat similar to the back E. M. F. of the carbon arc, except the latter maintains its constant value all the time the current is flowing, while the negative electrode resistance disappears after having been once overcome. Should the current entirely die away, however, the negative electrode resistance immediately reasserts itself, and a further application of high E. M. F. is necessary to disperse it. Should there be several negative electrodes in the same vessel of mercury vapor, the negative electrode resistance of each must be overcome, separately, before current can flow into that particular electrode.

When a mercury lamp is to be used on ordinary line voltages, 110 to 125 volt circuits, some means must be provided to produce the high E. M. F. necessary for starting. This is obtained by placing a coil of inductance in series with each lamp, which, during the operation of starting, at the break of the mercury stream, causes a momentary high E. M. F. which is sufficient to overcome the negative electrode resistance and to strike the arc, after which the line voltage is sufficient to maintain it.

Operating Circuits.—Some mercury vapor lamps are made to tilt themselves automatically in starting, others are started by tilting by hand. A wiring diagram of an automatic lamp is shown in Fig. 152. This shows two lamps operated in series. The automatic tilting is accomplished as follows: When current is switched on, a path is provided for it from the + line through a shunt circuit and a pivoted contact to the coils of an electro magnet to the — line through an adjusting resistance. This energizes the electro magnet, which draws up a plunger to which the tube is connected, one portion of the tube remaining fixed. This raises the tube and allows the mercury to run along its length, which provides a path for the current through the lamp. This current flows from the + line and the two inductance coils in series to the + terminal of the lamp, across the mercury to the — lamp terminal and through the voltage adjuster resistance to the — line.

The inductance coil now acts as an electro magnet, attracting an armature which lifts the pivoted contact of the shunt circuit, break-

ing the circuit, upon which the lamp falls back to its original position, and on the mercury stream being broken, the high E. M. F.

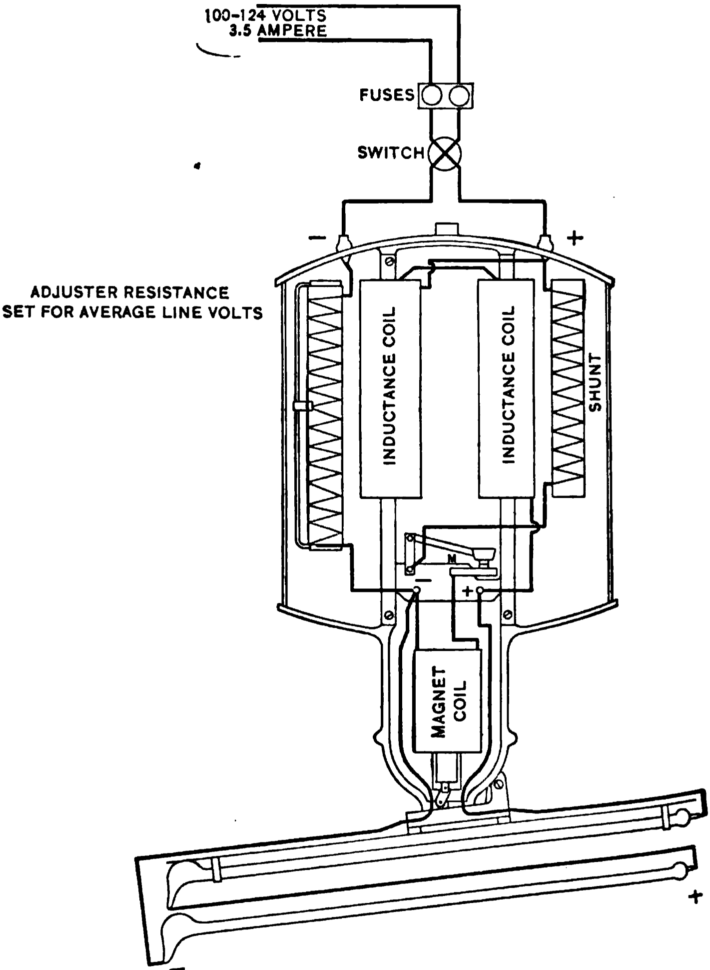


FIG. 152.—Wiring Connections of Type H Automatic Mercury Vapor Lamp.

induced by the inductance coils on the break, furnishes sufficient power to overcome the negative electrode resistance, and the arc is established.

The adjuster resistance shown on the left is for the purpose of regulating the voltage of the lamp to that of the line voltage.

Electrical Characteristics.—The ordinary voltages for which these lamps are designed to work vary between 100 to 240 volts. On the 120-volt circuit two Type H lamps of the Cooper Hewitt make are installed in series to avoid the long length of one tube, although if but one tube is used the same energy is consumed as when the two lamps are in series. The average current consumed per lamp is 3.5 amperes at 110 volts, giving 600 candle-power for the double lamp, or an efficiency of .64 watts per candle-power, which is about ⅙ of the power used in a carbon filament. To a certain extent the candle-power of the lamp is controlled by the diameter of the tube.

This lamp gives off a greenish light of very high intensity. The spectrum shows an absence of all red rays, and the light cannot be used when colors are to be compared, but makes a very satisfactory light for general illumination or reading.

36″ Electric Control, Form "N" Projector General Electric Co.

The exterior of this projector is similar to previous projectors of this type manufactured by the General Electric Co. with a few minor differences. The main differences in the interior are found in the lamp mechanism and in the method of control, this type being fitted for both hand and electric or "distance" control.

The electric control is effected by two motors in the base and on the turntable of the projector, one for training in azimuth and one for training in altitude, connected to a portable controller by flexible cable. The controller is provided with a sight bar which is arranged to move synchronously with the projector beam through the agency of hand wheels on the controller which operate the motors and which are so geared to the sight bar that the movements of it in altitude and azimuth correspond to the movements of the beam.

The Training System.

On the controller there are two separate hand wheels, one for each plane of control. By means of shafts connected to these wheels they

rotate simple commutating devices which are so arranged that the direct current of the supply is split up into currents having three-phase relation. Two leads, one of positive potential and one of negative, are led to each commutator from which three leads are taken and the current is so commuted that two of them have the same potential, while the third has the opposite. This will be understood by a consideration of Fig. 153.

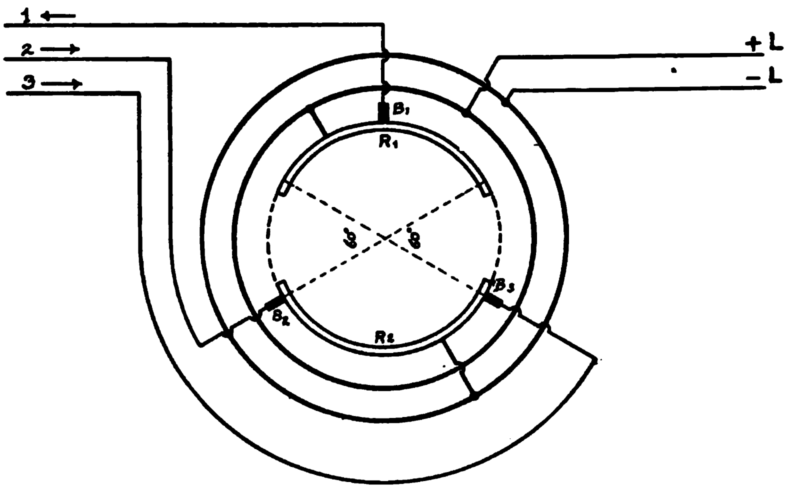


FIG. 153.—Commutating Device, Distant Control Searchlight.

The commutating segments are shown as R_1 and R_2, to which are connected respectively the line leads $+L$ and $-L$. Three brushes, B_1, B_2 and B_3, press against the commutator segments and they are connected respectively to the leads 1, 2 and 3. In the position shown, lead 1 would have + potential and leads 2 and 3 — potential. If the commutator is turned to the left through 60°, the brushes remaining stationary, 1 and 2 will be + and 3 will be —; if turned through 120°, 1 and 3 will be —, 2 will be +, etc.

The three leads 1, 2 and 3 from the commutator segments are led to a system of magnet coils, six in number, symmetrically arranged in a circle. These coils are fitted with pole pieces which project inwardly towards the center of the circle in which they are

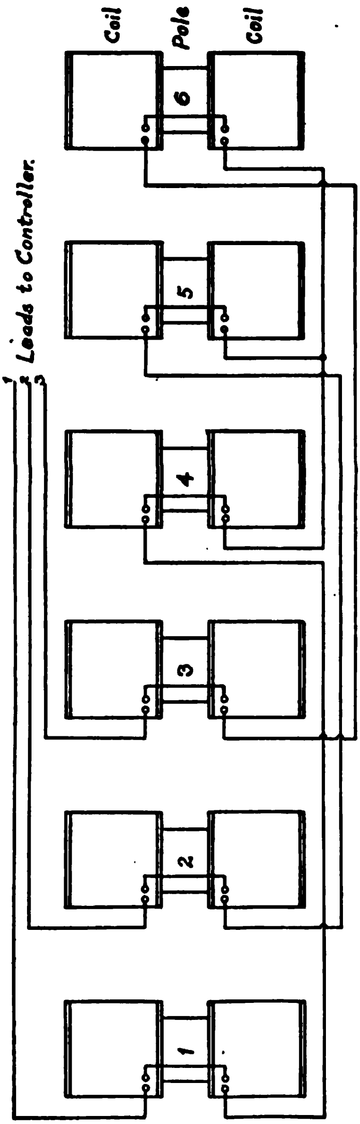


FIG. 154.—Developed View of Magnet Coils and Poles.

arranged. A developed view of these coils is shown in Fig. 154 and a sectional view in Fig. 155.

Within the space formed by the inwardly projecting pole pieces are fitted two field pieces at right angles to each other which are free to revolve. The ends of one of these field pieces are always of positive polarity, and those of the other end of negative polarity,

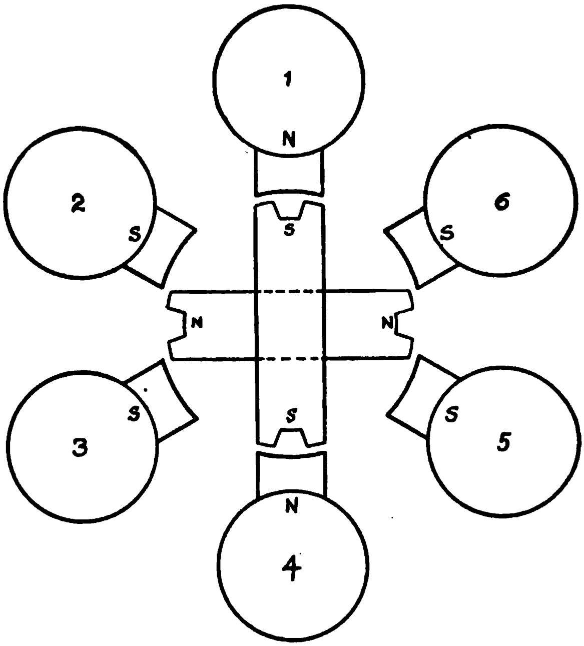


FIG. 155.—Sectional View of Magnets and Revolving Field Pieces.

produced by currents which always flow in the same direction in the coils which are wound on them.

Suppose the magnet coils are so wound that current flowing to the coil by the right-hand terminal and leaving by the left-hand one (facing the coil from the center), makes the pole of the coil of north polarity, and in the opposite direction makes it south polarity. Then if the current flows in the leads 1, 2 and 3 as indicated by the arrows in Fig. 156 it will be seen that coils 1 and 4 produce

north polarity and coils 2, 3, 5 and 6 produce south polarity. If leads 1 and 2 have current flowing to the left, or they are of positive potential, and lead 3 has current flowing to the right, or is of negative potential, coils 1, 4, 2 and 5 will produce north polarity and coils 3 and 6 will produce negative polarity.

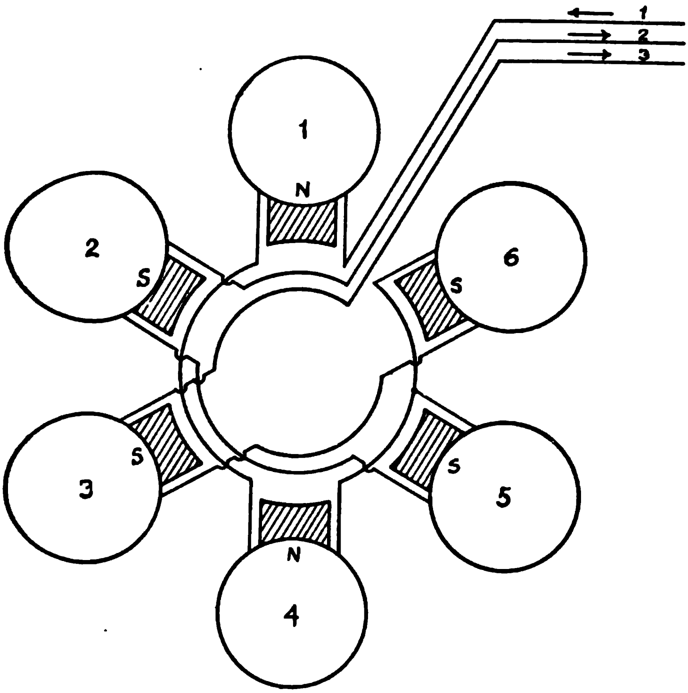


FIG. 156.—Sectional View of Magnet Coils and Poles.

As the commutator rings are turned, the currents in leads 1, 2 and 3 change in direction as previously described; consequently the polarities of the magnet coils change. As the polarity changes, the field pieces take new positions, turning with each change of polarity. Fig. 155 represents the zero position of the field pieces with the polarity of the coils due to the currents shown in Fig. 156. If the commutator is now turned 60° to the left, coils 1, 2, 4 and 5 will be of north polarity and coils 3 and 6 of south polarity and it will

thus be seen that the field piece will turn through an angle of 30° to the left, bringing the north poles of the field pieces directly opposite the south poles of coils 3 and 6, and the south poles midway between the north poles of coils 1 and 2, and 4 and 5. Each turn of 60° of the commutator thus causes the field piece to revolve 30°.

The following table shows the direction of current through leads as determined by the commutator, the polarity of the armature poles and the position of field poles:

Direction of Current through Leads Nos.			Polarity of Amature Poles Nos.						Position of Field Pole Nos.
1	2	3	1	2	3	4	5	6	
+	−	−	N	S	S	N	S	S	1
+	+	−	N	N	S	N	N	S	2
−	+	−	S	N	S	S	N	S	3
−	+	+	S	N	N	S	N	N	4
−	−	+	S	S	N	S	S	N	5
+	−	+	N	S	N	N	S	N	6
+	−	−	N	S	S	N	S	S	7
+	+	−	N	N	S	N	N	S	8
−	+	−	S	N	S	S	N	S	9
−	+	+	S	N	N	S	N	N	10
−	−	+	S	S	N	S	S	N	11
+	−	+	N	S	N	N	S	N	12

Each position of the field poles in the above table represents 30°, and after the 12 positions, or 360°, the operation is repeated.

The combination of the magnet coils and field pieces described above is called a *pilot motor* and in future, reference to it will be by that designation.

The pilot motor for the training system is mounted on the turntable of the projector and the leads from the commutating device

in the controller are brought to it by means of wires made up into a flexible cable.

The full horizontal training mechanism is shown in Fig. 157.

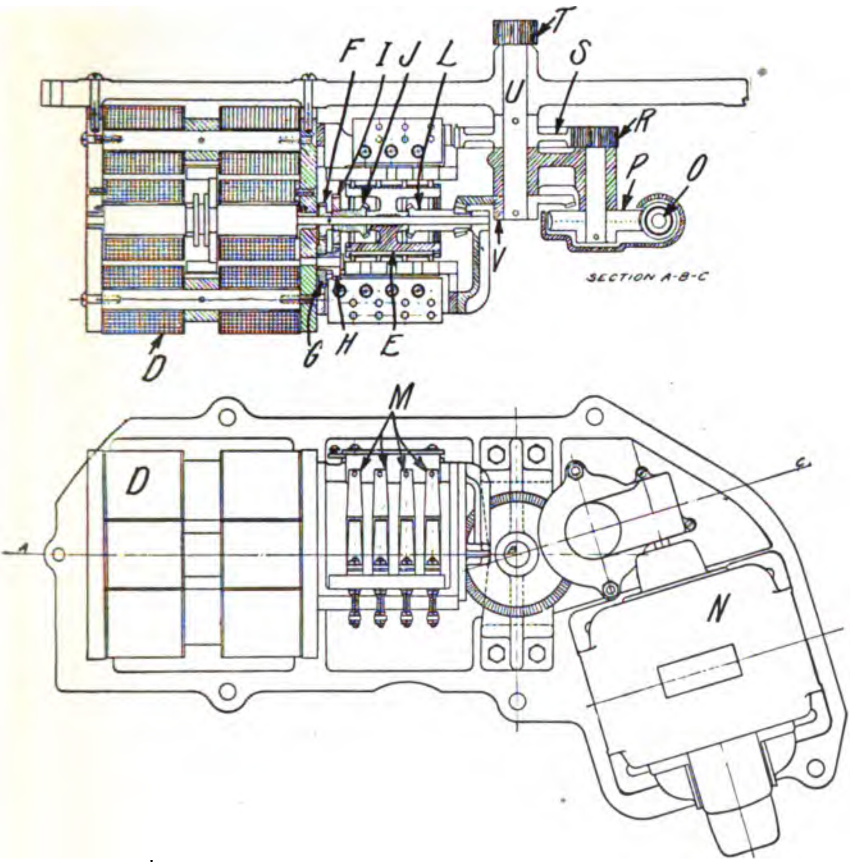


FIG. 157.—Assembly of Horizontal Training Mechanism of 36″ E. C. Projector.

Rotating the horizontal training hand wheel on the controller through 180° causes the revolving field piece of the pilot motor *D* in the projector to rotate through 90°. The field piece is connected to a cam cylinder *E* through the spur gears *F, G, H* and *I* and the

bevel box gearing J, K and L; K engaging with J and L, though not shown in the sectional view. This gearing is so designed that 90° revolution of the field piece produces about 15° revolution of the cam cylinder.

The movement of E operates the contact fingers M which connects the line current to the training motor N. The motor operates the projector through the worm O attached to the motor shaft, the worm wheel P, spur gears R and S and pinion T, connected to S, which engages in the circular rack on the turntable of the projector.

Connected to the shaft U, which connects the gears S and T, is the bevel gear V, which also drives the cam cylinder E, but in a direction opposite to that produced by the pilot motor. The cam cylinder E which makes the circuit between the line and the training motor thus has a motion which is dependent upon the relative motions of the pilot motor and training motor, the equivalent of which is always equal to zero. As soon as E begins to rotate, due to the rotation of the pilot motor, the projector begins to rotate and in so doing tends to revolve it back to its original position. The effect of this is to repeatedly make and break the line connection to the training motor, which trains the projector by a series of steps, and this will continue as long as the controller hand wheel is rotated. One-half turn of the controller handle turns the pilot motor 90°, the cam cylinder 15° and the gearing is so proportioned that the projector revolves 1°. To turn the projector 10°, it is only necessary to turn the controller handle through five complete revolutions. Reversing the direction of the controller handle causes the cam cylinder to make connections such that the training motor receives current in the opposite direction and the direction of rotation of the projector is reversed. The connections are such that turning the controller handle to the right, the projector turns to the right and vice versa. A slow motion of the controller handle produces a slow motion of the projector and a rapid motion produces a rapid motion of the beam. For the slow movements the motor is connected through resistances, which are short circuited for the faster speeds of training. If the rotation of the controller handle is relatively faster than the rotation of the projector, there will be a slight

lag, but it will catch up and stop at the proper place corresponding to the position in which the controller handle is left.

Vertical training is effected in the same manner as the horizontal, through the agency of a hand wheel on the controller and a pilot motor and motor for vertical training. This mechanism is mounted in a watertight case on the turntable and the driving pinion engages a segment of a circular rack which is connected by brackets to the body of the projector.

In addition to the electric control, the projector is fitted with both vertical and horizontal wheels for hand control.

The Controller.

The mechanism of the controller is contained in a watertight case which is of such weight and dimensions as to be easily portable. It contains the *commutating devices,* the *operating wheels,* a *locking magnet,* the *sight bar* and the gearing by which the sight bar is moved synchronously with the projector beam. The same motion of the control wheels that operates the commutating devices serves to move the sight bar by means of a system of gearing which is readily seen by an inspection of Fig. 158.

Locking Magnet.—This is for the purpose of locking the operating wheels when current on the training motors fails and the wheels cannot be moved when the magnet is de-energized. This is to prevent any motion of the sight bar without a corresponding motion of the beam and tends to preserve the orientation of the sight bar and beam. In case the rotation of the hand wheels is relatively greater than the speed of the beam, the locking magnet circuit is broken by the opening of its circuit through one of the cam fingers operated by the pilot motor and the wheels remain locked until the beam can catch up. An inspection of Fig. 159, showing the wiring diagram, will show how this is accomplished, the magnet receiving its positive potential from the left-hand finger on the cam through terminal No. 9 in couplings and in the controller.

Orienting.—The projector beam and line of sight are conveniently oriented by bringing them on a common object at some distance

and then clamping the projector to the electric control. The hand wheels are provided with clutches for this purpose and any slight variation in alignment may be corrected by thumb screws on the controller.

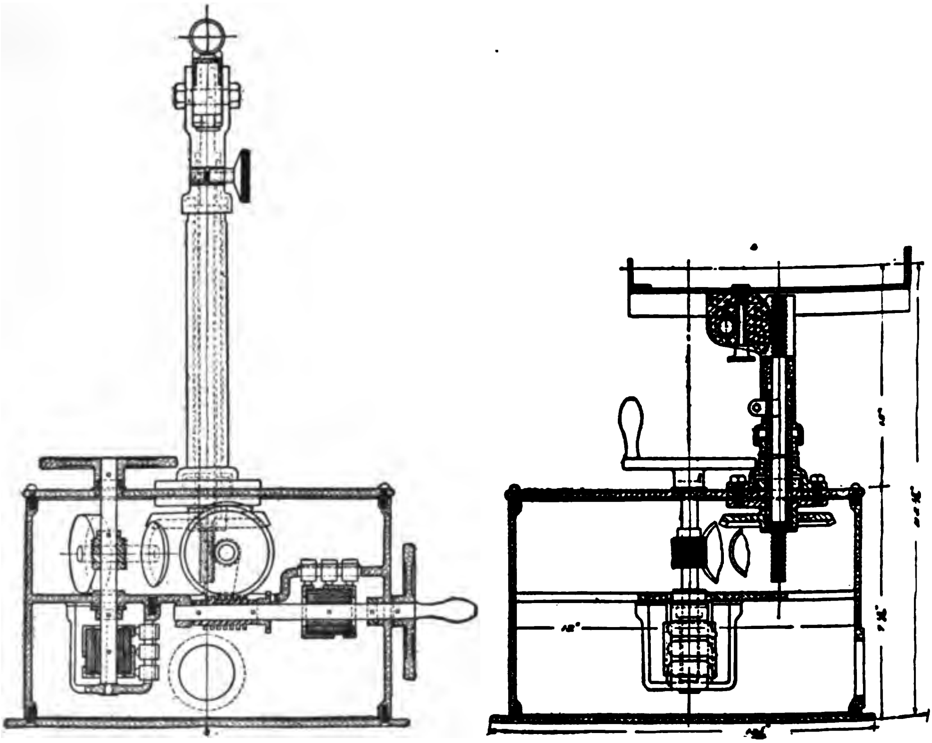


FIG. 158.—Form N Projector Controller.

Lamp.

The lamp in this type of projector differs from those which have been previously manufactured by the General Electric Co. The series magnet provided for striking the arc has been dispensed with and the carbons are caused to approach or recede from one another according to the arc voltage by separate feeding magnets. Each feeding magnet operates a feeding screw, one feeding the carbons together, the other feeding apart.

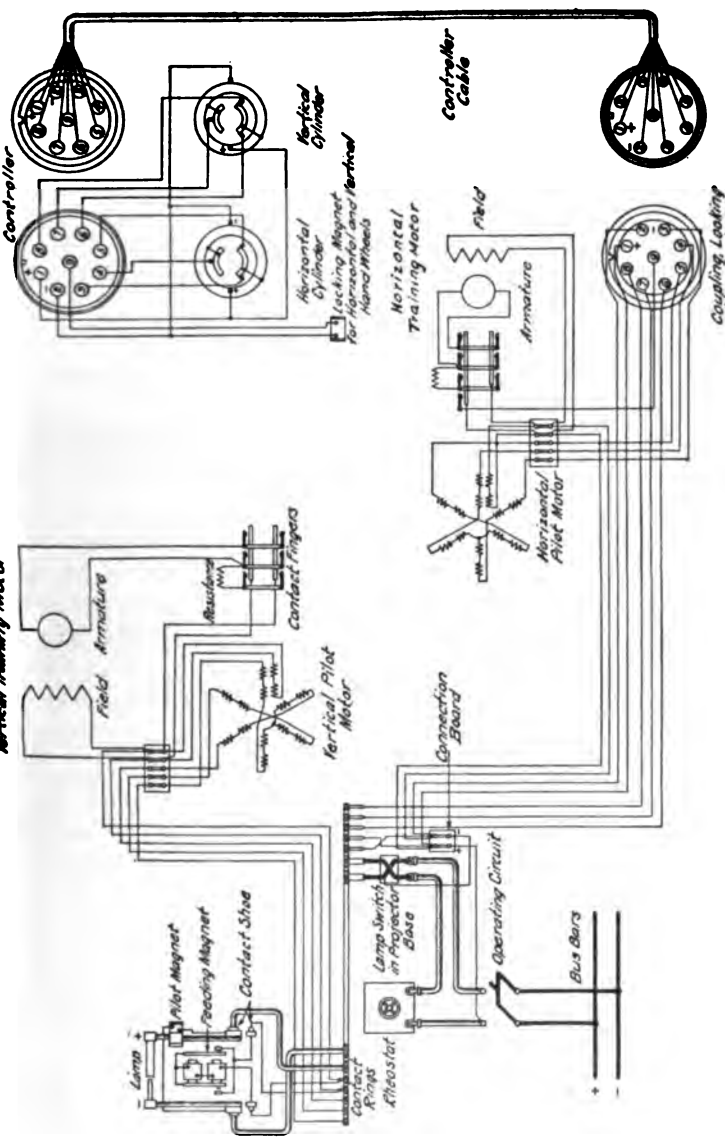


FIG. 159.—Connections of Electric Control Projectors 36″ Form N. Gen. Elec. Co.

Fig. 159 shows the working principle of the lamp. The two feeding magnets are shown connected in series directly across the line, and though they operate under the ordinary arc voltage, they must be designed for the full line voltage which exists before the arc is established. They are equipped with two armatures, and each armature controls the mechanism for feeding in one direction. These armatures of the feeding magnets are selectively operated by a pilot magnet which has two armatures connected by means of links to steel latches which lock or unlock the armatures of the feeding magnets.

The pilot magnet is differentially wound by two windings, one a shunt winding across the terminals of the arc, the other in series with the arc and carrying the whole arc current.

Lamp Operation.—Assuming that the carbons are in place and some distance apart, the operation is as follows: When the main line switch is closed, the shunt winding of the pilot magnet receives full line voltage and a maximum flux is caused through the magnet. This causes both the right- and left-hand armatures of the pilot magnet to be attracted. The right-hand armature releases one of the armatures of the feeding magnets and the left-hand armature locks the other armature of the feeding magnet. The released armature, through its make and break and pawl and ratchet, as in the previous type of lamps, acts on one feeding screw and the carbons are fed together. When the carbons touch, current passes through the series winding of the pilot magnet, and owing to the differential winding, and to the fact that the voltage at the shunt-winding terminals is reduced to about 30 volts when the carbons first touch, the flux is reduced to a minimum. At this reduced flux both pilot magnet armatures are released, with the result that the right-hand armature now locks the one that was at first released, and the left-hand armature releases the one that was at first locked. This released armature, through similar mechanism to the other, acts to feed the carbons apart.

As the carbons are fed apart, the voltage gradually increases and the current decreases, and with this type of lamp when the arc voltage is about 60 volts and current 110 amperes, the flux through the pilot magnet has increased a sufficient amount to attract the

left-hand armature of the pilot magnet. This locks the feeding-apart armature and under these normal conditions of voltage and current both feeding magnet armatures will remain locked and the carbons will cease to be fed.

As the arc burns away the carbons, the current is reduced and the voltage is increased and the flux through the pilot magnet increases to such an extent that the right-hand pilot magnet armature is attracted. This releases the feeding-together armature, and the other being locked, the carbons are again fed towards one another until normal conditions are reached. Any increase in arc voltage above normal increases the pilot magnet flux and releases the feeding-together armature, and any decrease reduces the pilot magnet flux and releases the feeding-apart armature, and the feeding continues until normal conditions are reached at the arc.

Adjustment.

In adjusting the lamp, the feed-apart armature of the pilot magnet should be adjusted by means of its controlling spring so that it will be released when the arc voltage has reached 45 volts, feeding apart until it is attracted at 52 volts.

The feed-together armature of the pilot magnet should be adjusted by its spring so that it will be attracted at 62 volts, feeding together until 54 volts have been reached.

In adjusting either of these pilot magnet armatures, the other should be held in a position where it will lock its feeding magnet armature.

The jaws of the locking latches should be kept clean and occasionally a small amount of clock oil should be used on them. All parts of the lamp mechanism should be kept clean and free from carbon dust and the points of the feeding magnet contact screws especially should be kept bright.

CHAPTER XX.

MEASURING INSTRUMENTS.

There are many laboratory methods for measuring electrical quantities and testing electrical machines, but on shipboard measurements are limited by the instruments furnished; these only being sufficient in a most general way for measuring the three electrical quantities of resistance, difference of potential and current.

The instruments ordinarily furnished to ships for electrical measurements are voltmeters, ammeters, testing sets and magnetos. In addition, on some ships may be found ohmmeters, whose principle and use will also be described.

Instruments.

Every electrical effect has a cause, and the effects produced are made the basis of the construction of electrical instruments. The effects generally taken advantage of are those falling under the head of static, heating, chemical or magnetic.

Of these effects, the last, that of magnetic, or electromagnetic, is the governing principle of the instruments furnished for use on shipboard. Instruments based on static, heating or chemical effects are used as standards to a greater or less degree and their principles will be briefly touched on.

Electrostatic Effect.—If there is a difference of electrostatic potential existing between two conductors, they tend to attract one another. If one is freely suspended while the other is immovable, the suspended one in approaching the other may be made to carry a pointer which will indicate the difference of potential. Voltmeters made on this principle are for certain ranges the most accurate, as they absorb no current, and there is no fall of potential due to the instrument itself.

Electrostatic voltmeters are made for measuring high potential difference and they are not usually suitable for measuring small voltages. Electrostatic voltmeters may be used to measure current by the fall of potential through a known resistance.

Heating Effect.—The fall of potential in a conductor due to its own resistance represents a loss of energy of electric current which reappears as heat, and which raises the temperature of the conductor. The amount of heat developed may be measured, and from this the current producing the heat may be measured.

The heat produced in a conductor causes expansion of the conductor in reference to other conductors through which the current is not flowing. This expansion may be measured and the temperature thus found, and therefore the current measured which produced it. In the Cardew voltmeter, the conductor consists of a wire of high resistance, three or four yards in length. The current that flows through this conductor is proportional to the E. M. F. at the terminals, and this current, owing to the heat produced, causes the conductor to lengthen. As the conductor expands, it sets in motion a train of wheels moving a pointer which indicates the difference of potential.

Electrochemical Effect.—When a current passes through a liquid (not an elementary substance), the liquid is decomposed, part going to that conductor where the current enters the liquid, and part where the current leaves the liquid. If the electrodes and the electrolyte are prepared according to some standard specifications, the same current in the same time will always liberate the same amount of matter. This matter can be measured and therefore the current determined.

This effect is very accurate and is used in this country as a standard for measuring currents (see under Ampere). In its ordinary form it cannot be used as a voltmeter, nor directly as an ammeter, unless the current remains constant for the whole time.

Magnetic Effect.—Several classes of instruments are made depending upon magnetic or electromagnetic effect. Some depend on the mutual attraction or repulsion of conductors carrying current due to the magnetic fields set up around them; others depend upon the reaction between a magnetic field due to some outside source and the magnetic field set up around a conductor carrying a current lying in that field, and still others depend upon the attraction between a conductor carrying a current and the field induced by it in some soft-iron core.

Siemen's Dynamometer.

An example of the class of instruments based on magnetic effects is the well-known Siemen's electrodynamometer, which is of interest on account of its being used as a standard, and on account of its being adaptable for either a voltmeter or an ammeter, or even indeed as a wattmeter. This dynamometer consists of two coils at right angles to each other, one being stationary while the other is free to revolve. The movable coil hangs from a thread secured to a spiral spring, which in its normal condition allows the coil to remain at rest perpendicular to the stationary coil. Current is sent through the two coils and the magnetic fields set up around the conductors tend to move the two coils so as to make their planes parallel. This tendency causes the movable coil to rotate against the tension of the spiral spring, and it comes to rest in a position determined by the relative strengths of the fields and that of the spring. The amount of twist given the spring in order to bring the movable coil back to its zero position is a measure of the current in the coils. The spring is twisted by means of a milled head which carries a pointer travelling over a scale which indicates the current.

If both coils are made of a large number of turns of fine wire, it can be used as a voltmeter by connecting a high resistance in series with it. It still measures the current, but this is proportional to the E. M. F. at the terminals and the force is a measure of the E. M. F.

This form of instrument could not be used on board ship, for it must be carefully leveled, and it is not direct reading, so it requires time and very careful handling, and is of not much use if the current fluctuates. It is of special value, though, for calibrating other instruments, and its permanence and reliability depends only on the spring, which experience has shown is practically unchangeable.

The voltmeters and ammeters furnished for use on shipboard come under the second class given under the heading, magnetic effect, but before they are described in detail, the general use and method of connecting up voltmeters and ammeters will be considered.

The Use of Voltmeters and Ammeters.

An ammeter, as its name implies, measures current, while a voltmeter measures voltage or difference or fall of potential. As constructed, most voltmeters are simply special forms of ammeters, though, in some cases, the opposite might be said.

An ammeter measures directly the strength of the current flowing through its coils, and in order that the current flowing in a circuit may not be altered by the introduction of the instrument which measures it, it is evident that the ammeter should have as little resistance as possible.

A voltmeter measures the difference of potential between two points, and it is clear that only so much of the current flowing as is necessary for the proper sensitiveness of the instrument should be diverted through the voltmeter. The voltmeter thus should have a very high resistance both for the sake of economy and accuracy. If a high resistance is connected in series with a sensitive ammeter that will measure small currents, then the current passing would be proportional to the voltage at the terminals and the instrument could be made to indicate volts.

The current flowing through an ammeter is proportional to the difference of potential at the terminals of the instrument, and from this it might appear that the difference of potential between two points might be measured by simply joining an ammeter between the two points, recording the number of amperes flowing and from the resistance of the ammeter infer the difference of potential between the points. But if such a low resistance as that of an ammeter be connected between the two points, the total current between those points would be materially changed and the very act of connecting the ammeter would alter the difference of potential required.

For instance, if an ammeter was connected to the terminals of a battery with no other circuit, it would not indicate the E. M. F. of the battery, but what could be obtained would be the fall of potential through the instrument. If the battery had a separate circuit, and it was desired to measure the fall of potential through that circuit, it is evident an ammeter would not be available for doing it by connecting it across the terminals of the battery. The

act of connecting the ammeter would reduce the current in the external circuit, and its resistance remaining unchanged, the difference of potential would be considerably lowered. What is wanted is the difference of potential before the instrument is introduced and what might be obtained is the difference of potential after the instrument is connected. The less current, then, that is absorbed by the instrument measuring difference of potential, the more accurate it is, and it is seen that as the ammeter has more and more resistance it develops into a voltmeter.

Further reasons for the peculiar construction of voltmeters and ammeters and the objects to be attained by them may be illustrated by a simple example.

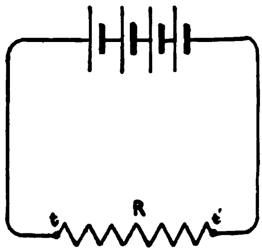


FIG. 160.

In Fig. 160 is represented a typical battery circuit, consisting of a few cells, leading wires and a resistance R joined between the terminals t and t'. If the E. M. F. of the battery is constant, there will be a constant current flowing in all parts of this circuit, the same through the battery, through the connecting wires and through R; this current depending on the E. M. F. of the battery and the resistances of the several parts. Suppose the E. M. F. of the battery and all the resistances are accurately known, then the current flowing in any portion of the circuit will be known, and the potential may be calculated for any two selected points. These results can be obtained absolutely without the use of instruments.

Let

$E = 12$, the E. M. F. of the battery;
$r = 2$ ohms, internal resistance of the battery;
$r' = 1$ ohm, resistance of leading wires;
$R = 3$ ohms, resistance between t and t';

then

C, the current flowing in any portion of the circuit, by Ohm's law $= \frac{12}{1 + 2 + 3} = 2$ amperes.

By the same law, also, the difference of potential between t and t' is $2 \times 3 = 6$ volts.

Now suppose it is wished to measure these values by instruments, the question becomes, where should they be placed in circuit or how should they be connected in order that the values already known to be correct should not be materially changed. It has already been shown that to measure a current, the current must pass through the instrument, and in order that the existing current may not be changed, the ammeter must necessarily have a very low resistance and be directly connected in series with the circuit. If the resistance is not low but still connected in series, the current value would be materially changed. If the resistance is low, but not connected in series, but as a shunt between two points, the external resistance will be reduced, thus increasing the battery current.

To measure the difference of potential between two points, the instrument must be joined as a shunt to those points, and in order that the current between them may not be greatly changed, the resistance of the voltmeter must be very great.

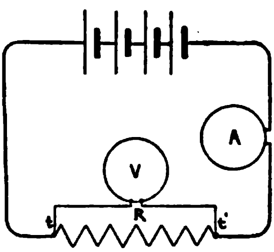


FIG. 161.

The connection of the instruments for measuring the battery current, and the difference of potential between t and t' is shown in Fig. 161.

A represents the ammeter and V the voltmeter, A connected for measuring the total battery current, and V for measuring the difference of potential between t and t'. Suppose A had a resistance of .01 ohm and V a resistance of 15,000 ohms. If V had been inserted in A's place to measure the current, the value of C would be

$$C = \frac{12}{1 + 2 + 3 + 15{,}000} = .00079 \text{ amperes.}$$

If A had been used to measure the difference of potential between t and t', C would be

$$C = \frac{12}{1 + 2 + \frac{3 \times .01}{3 + .01}} = 3.98 \text{ amperes,}$$

and the difference of potential between t and t' would be
$3.98 \times (.0099 = \text{joint resistance between } t \text{ and } t') = .0394$ volts.

If A were put in V's place and V in A's, C would be

$$C = \frac{12}{1 + 2 + \frac{3 \times .01}{3 + .01} + 15{,}000} = .00079 \text{ amperes}$$

and the difference of potential between t and t' would be

$$.00079 \times (.0099 = \text{joint resistance}) = .0000078,$$

figures which do not bear any resemblance to the real values, and which show the effect of connecting up the instruments wrong.

If they are connected as in the figure, C would be

$$C = \frac{12}{1 + 2 + \frac{3 \times 15{,}000}{3 + 15{,}000} + .01} = 1.9963$$

and the difference of potential between t and t'

$$1.9963 \times (2.9994 = \text{joint resistance}) = 5.9877,$$

results which differ slightly from the values known to be correct.

With this arrangement the fall of potential around the circuit would be

	Through the battery	$2 \times 1.9963 =$	3.9926	volts.
	" " wires	$1 \times 1.9963 =$	1.9963	"
	" wire t, t'	$3 \times 1.9963 =$	5.9889	"
	" A	$.01 \times 1.9963 =$	.0199	"
or	Total fall	$=$	11.9977	"

Care in Using and Connecting Voltmeters and Ammeters.—It has been shown by figures what the result would be by using a voltmeter for an ammeter or vice versa, but they do not tell the whole story. There ought to be no difficulty in distinguishing one from the other, for they are always marked. The reading of the scale will always be a guide, as they are marked either volts or amperes.

If an ammeter were used for a voltmeter on a high potential circuit, on account of its low resistance and the high potential a very large current would be apt to flow, damaging not only the instrument but other parts of the circuit. If a voltmeter was used as an ammeter, very little current would flow, on account of the high resistance, unless the E. M. F. was very high, in which case the delicate coils of the voltmeter might be burnt out.

Ordinarily it does not injure voltmeters or ammeters to connect them up wrong as far as polarity goes, the pointer simply indicating in the wrong direction. Too much current sent suddenly through an instrument may throw the pointer violently against its upper stop, rendering it liable to be bent. More current than is designed for may cause the coils to heat to a dangerous degree, burning or destroying the insulation of the conductors.

In making connections with a voltmeter or ammeter, it is better to make the connections on the instruments first, and to the circuit last, and still better to have a switch in the circuit, so all connections may be made without danger of injuring the terminals by the arc which might otherwise be formed.

Instruments should be used with care and judgment at all times. The best ones are made with great care with small pivots and jewel bearings, and rough handling is apt to dull the points or crack the jewels. Rough handling is also liable to weaken the permanent magnet in instruments like those of the Weston type which will cause incorrect readings.

Instruments should not be placed close to a running generator or motor, on account of the danger of having the magnetic fields distorted by the stronger fields, nor should instruments with permanent magnets be placed close to one another, not within 2 to 3 feet.

Weston Voltmeters.

The general form invariably used in the service on shipboard is that of the Weston type, being a development of the early d'Arsonval galvanometers. Two forms are usually supplied, one the station type for use on permanent switchboards, and the other a portable instrument for measurements about generators, motors, or measurements for resistance or fall of potential in different parts of a circuit. They are constructed on the same principle, already quoted under the second class of instruments given under the heading *magnetic effect.*

The permanent magnetic field is produced by a permanent steel magnet of peculiar form, half circular, half horse-shoe (see Fig. 310); the outside form of the face of the portable instrument

being in general the shape of the magnet. The form of the pole pieces is also peculiar and is such that the deflecting coil moves in a constantly uniform field, and this is necessary in order to have the deflections follow the proportional law. Between the poles of the magnet is pivoted on very sharp points resting on jeweled bearings, a very fine light rectangular coil of wire, as shown in Fig. 162. The motion of this coil is restrained by two fine spiral springs, each something like the hair spring of a watch, one at the top and one at the bottom, through which the current is led into and out of the instrument through the pivoted coil.

The index that registers the reading on the face is a long thin aluminum pointer and is secured to the top of the coil, moving with the coil as it is deflected. When no current is flowing, the action of the springs keeps the coil in its zero position, the pointer then registering zero in the scale.

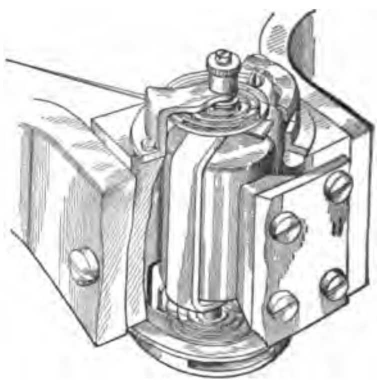


FIG. 162.—Coil and Poles of Weston Instruments.

Within the movable coil is a central cylindrical core of soft iron, this tending to strengthen the magnetic field of the permanent magnet, or rather tending to reduce the resistance of the permanent magnetic circuit. The movable coil is wound on a light copper frame, which in addition to serving as a support for the coil acts as a magnetic brake, moving as it does in an intense magnetic field and having currents induced in it opposing its motion. This makes the instrument practically "dead beat." As soon as current flows, the pointer at once takes a position to indicate the voltage and there is no "hunting" or fluctuating of the pointer.

The movable coil has a resistance of about 60 ohms and a full deflection is produced when a difference of potential of about .6 volt is applied to the coil. When measuring higher voltages than this it is necessary to insert resistances in series with the coil,

the added resistance being proportional to the maximum difference of potential to be measured. The inserted resistance must be calculated for a resistance of $\frac{60}{.6} = 100$ ohms for each scale division. To measure 100 volts would require a resistance of $\frac{60}{.6} \times 100 = 10{,}000$ ohms. This resistance is usually a coil of platinoid or manganin wire placed inside the instrument case, and as this alloy has a very low temperature coefficient, the temperature error is inappreciable and the instrument can be left continuously in circuit; the loss of power owing to the high resistance being very small.

When this voltmeter is connected to the two points of different potential, there is a temporary magnetic field set up around the movable coil, and the coil experiences a pull on one side and a push on the other tending to make it rotate, and it takes a position dependent on the resultant of the forces due to the two magnetic fields and the tension of the springs. The same current always produces the same field and the same deflection, so by proper calibration or comparison with other standards, the proper number of volts may be marked off on the scale.

As the coil moves practically in a uniform field, the subdivisions on the scale are very nearly equal.

The portable voltmeters are usually calibrated for and marked with two scales, one for high reading, and the other for low reading. The low-reading scale is made available and effective by placing properly wound resistance coils in series with the movable coil, this arrangement necessitating a third terminal on the instrument.

Weston Ammeters.

The ammeters furnished for ships' use are generally of the Weston type (see Fig. 163), and their governing principle and construction is exactly similar to that of the Weston voltmeter, the scale being marked to register amperes in place of volts. In some of the earlier forms it was usual to lead the whole current to be measured to and through the ammeter, in the inside of which was a resistance slightly greater than that of the leading wires, and the current that flowed through the ammeter coils was taken as

a shunt from the ends of this resistance. Only a portion of the main current flowed through the instrument coils, which acted in all respects exactly as a voltmeter measuring the difference of potential between the points to which it was connected.

FIG. 163.—Weston Portable Ammeter.

Ampere Shunt.

In order to obviate the necessity of leading the heavy wires to the instrument on the panel board, a later practice is to insert the resistance that was formerly placed in the instrument directly in the leads in some convenient place on the switchboard. Such a resistance is called the **ampere shunt,** and it consists of a resistance slightly greater in value than the main conductors in which it is inserted. A general form of this resistance is shown in Fig. 164.

Two copper terminals, *a, a,* are soldered to the ends of the main conductor *b, b*. Between these copper terminals are strips of metal alloy *c,* soldered in place to the terminals; the resistance being in strips to better allow for ventilation. The leads to the ammeter terminals *d, d,* are brought to the copper terminals and clamped at *e, e.*

On account of the slight increase in resistance of the metal strips over the rest of the conductor, a small proportional part of the

current is shunted through the ammeter, which thus practically measures the difference of potential between the ends of the resistance, but this, being proportional to the main current flowing, by proper calibration measures the whole current.

It is very necessary that the shunt should have a practically constant resistance as it may carry constantly varying currents and this is effected by using an alloy of low temperature coefficient, such as platinoid or manganin.

It must be remembered that the ammeter is calibrated with a certain resistance in the leading wires from the terminals of the resistance to the instrument, and the resistance of these wires must

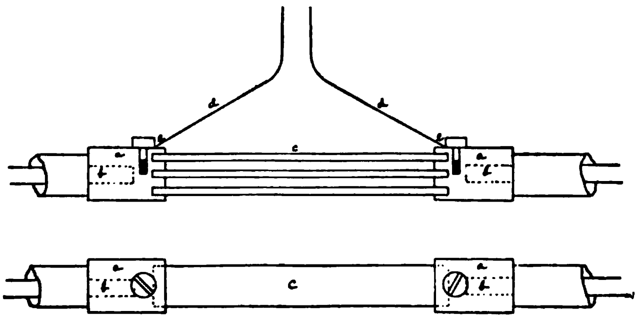


FIG. 164.—Ampere Shunt.

not in any way be changed by splicing or cutting, for the main resistance remaining constant, it is evident that the resistance of the leading wires must also remain constant if the instrument is to correctly record.

There must be perfect electrical connection between the shunt and the main conductor and between the shunt and the ammeter leads. Any resistance due to a bad contact in the former case would cause the ammeter to read too high and in the latter case too low.

The coil of the instrument is the same for all ranges and the full deflection of the needle is obtained when the difference of potential at the terminals is .06 volt. The resistance of the shunt is such that this difference of potential, about .06 volt, exists when the

shunt is carrying the maximum current and the resistance of the shunt is varied by changing the number of strips of alloy in it, their lengths remaining the same.

Resistances and Shunts.

The same instrument may be used either as an ammeter or a voltmeter by the use of resistances properly constructed and connected in circuit with it. If the deflecting coil has a resistance of 60 ohms and a full scale deflection is produced when .6 volt is applied at its terminals, .01 ampere would flow through the coil. To measure any potential difference greater than .6 volt, resistance must be added in series with the deflecting coil.

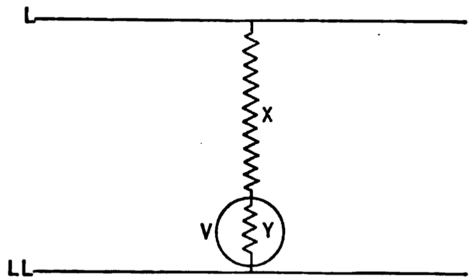


FIG. 165.—Resistance for Voltmeter Connections.

Suppose it was required to have the full scale deflection represent 150 scale divisions or to indicate 150 volts, a resistance of 14,940 ohms would have to be added in series with the 60 ohms of the deflecting coil. This is determined as follows:

In Fig. 165 Y represents the deflecting coil to which the deflecting needle of the voltmeter V is secured. The added resistance is X, and X and Y are connected in series across the line L, LL, across which the potential difference is required. In reality X is enclosed by the voltmeter case.

If the potential difference across the line is 150 volts, the current through the resistances X and Y is

$$\frac{150}{X+60}. \tag{1}$$

The fall of potential across Y is .6 volt and across X is $150 - .6 = 149.4$ volts. The current through X is

$$\frac{149.4}{X}. \tag{2}$$

As the current is the same in both instances (1) = (2), or

$$\frac{149.4}{X} = \frac{150}{X+60},$$

or $X = 14{,}940$ ohms.

If the potential difference across the line is 100 volts, the current through the resistances X and Y is $100 \div 15{,}000$ amperes, and the drop across the deflecting coil is $(100 \div 15{,}000) \times 60 = \frac{6}{15}$ volt. If .6 volt represents 150 scale divisions, $\frac{6}{15}$ volt would represent $\frac{6}{15} \times \frac{150}{.6} = 100$ scale divisions. 100 volts would then produce a scale deflection of 100 divisions, and if 150 scale divisions represented 150 volts, 100 scale divisions would represent 100 volts.

Shunts.—To have the scale of the instrument indicate directly in amperes, it is necessary to add a shunt resistance to that of the deflecting coil.

Suppose the deflecting coil had a resistance of 20 ohms and a full scale deflection was produced when a potential difference of .2 volt existed at its terminals, then .01 ampere would flow through the coil. Suppose it is required to have 100 amperes represented by a full scale deflection, then a certain resistance must be connected as a shunt to the deflecting coil and through which the current to be measured must flow.

In Fig. 166 the main current whose strength is to be measured flows in L, L, in which is inserted the shunt resistance S, to which the terminals of the deflecting coil of the instrument are connected.

For a full scale deflection, the potential drop across S and Y (neglecting the resistance of the connecting wires) is .2 volt, and if a current of 100 amperes, which is to be represented by a full scale deflection, is flowing, the resistance of S must be $.2 \div 100 = .002$ ohm. With this resistance, different currents through S would produce different potential drops across Y. Thus 50 amperes would give a drop of $50 \times .002 = .1$ volt, and as .2 volt gave full scale deflection, .1 volt would give half scale deflection, and if full scale deflection represented 100 amperes, half scale deflection would represent 50 amperes, which was the amount flowing.

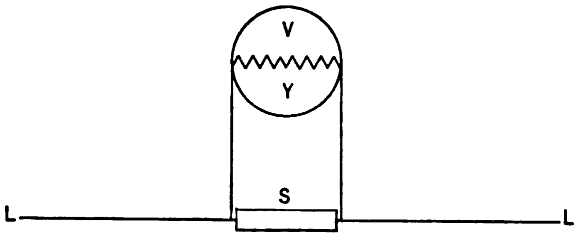


FIG. 166.—Shunt Resistance for Ammeter Connections.

Millivoltmeters.—If the scale in the above instrument had been marked in volts instead of amperes, the full scale deflection would be marked $100 \times .002 = .2$ volt or 200 millivolts. If 50 amperes were flowing, the potential drop across Y would be $50 \times .002 = .1$ volt or 100 millivolts, and the half scale deflection would represent 100 millivolts. Thus a millivoltmeter with a shunt resistance may be used to indicate amperes directly by marking the scale in amperes rather than in millivolts. By using different values of shunt resistance, the same throw of the pointer in a millivoltmeter may represent different current values, and the scales may be marked according to the value of the shunt used.

Thus, suppose a .001 ohm shunt was used, a full scale deflection would represent $.2 \div .001 = 200$ amperes, and a .004 ohm shunt would represent $.2 \div .004 = 50$ amperes. Thus the instrument, instead of being marked in millivolts, could have the same scale

marked for three different current values; the maximum in each case being 50, 100 and 200 amperes.

The Testing Set.

The testing set for measuring and comparing resistances ordinarily consists of a battery of a few cells, a galvanometer, and a combination of resistance coils of known value. The principle of all resistance testing sets is that of the Wheatstone bridge.

Before explaining the principle of the Wheatstone bridge it will be first necessary to explain the action of the galvanometer, as this instrument has been mentioned in several preceding tests, and will find constant reference in the future.

The Galvanometer.—This is an instrument for indicating and comparing currents, not to measure them, except in an indirect way. One of the most delicate instruments for showing the effect of an electric current is an ordinary magnetic compass needle. It will be remembered that the definition of the ampere was based on the effect a current of electricity produced on a magnetic pole. It will be well here to repeat the definition as finally determined on. If a conductor one unit in length (one centimeter) be bent into an arc of a circle one unit in radius (one centimeter) and a unit magnetic pole be placed at the center, then the current through such a conductor will be one unit of current if it acts on the unit magnetic pole with a force of one dyne. The effect of the current is inversely proportional to the square of the distance, r the radius, from the magnetic pole. Evidently there could be no closed circuit in such a conductor, and to make one complete turn around the pole, there would have to be a conductor in length equal to $2\pi r$. The force then in dynes which a current C would exert on a unit pole due to one complete turn would be expressed by the equation $\frac{2\ rC}{r^2} = f$, and if the coil consisted of n complete turns, would be $\frac{2\pi nC}{r} = f$.

If such a coil surrounds a magnetic needle, each unit of strength of the needle will be acted on by a force of f dynes. The needle

is held in the magnetic meridian by the horizontal force of the earth's magnetism, this force designated by H acting on each unit of strength of the magnet. If the needle is acted upon simultaneously by these two forces it will take a position at an angle δ from the meridian that will represent the resultant of the direction of the two forces. If the coil is in the meridian, the force due to the current acts at right angles to it, and the force due to the earth acts in the meridian. Fig. 167 represents the forces acting on the needle, NS being the meridian, δ the angle of deflection, H the horizontal force of the earth tending to hold the needle in the meridian and f the force due to the current flowing in a coil in the meridian over the needle. It is evident, then, that

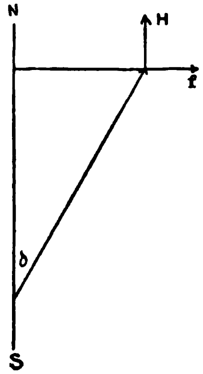


FIG. 167.
Forces Acting on Needle in Tangent Galvanometer.

$$f = H \tan \delta,$$

or

$$\frac{2\pi n C}{r} = H \tan \delta.$$

These quantities all being known, it follows that C in CGS units $= \frac{r}{2\pi n} H \tan \delta$, or C is proportional to $\tan \delta$. This is the principle of the tangent galvanometer.

The Wheatstone Bridge.

The Theoretical Bridge.—The bridge (Fig. 168) consists of four arms 1-2, 2-3, 3-4 and 4-1, in three of which are variable coils of known resistance, and in the fourth, the unknown resistance X is placed. A battery B of a few cells is connected to 1 and 3, and a galvanometer G is connected to 2 and 4.

Let A, B, C and X represent the four resistances and C_a, C_b, C_c and C_x the currents in those resistances at any time.

A and B usually contain coils of resistance varying by multiples of 10, as 1, 10 and 100, and 10, 100 and 1000, and they are called the *balance* arms. The arm C contains numerous coils of resistance of such values that any whole integer may be made, and this is called the *rheostat* arm.

The current from the battery divides at 1, flows through A and C, B and X to 3 and thence back to the battery. When there is a difference of potential between 2 and 4, current will also flow in that branch, either towards 2 or towards 4, depending on the relative resistances of A and B. If current does flow through the galvanometer, it will be shown by the needle being deflected, but if there is no difference of potential between 2 and 4, no current will flow in that branch and the needle will remain at rest. When this happens a *balance* is said to be established between the four arms, and as this condition always exists in making a measurement, it is

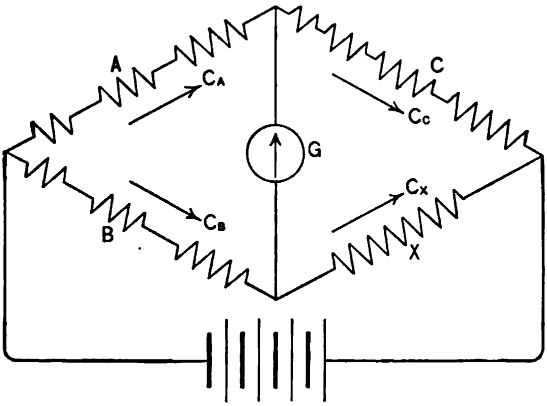


FIG. 168.—Connections of Theoretical Wheatstone Bridge.

called a ***null*** method. There are keys in the battery circuit and in the galvanometer circuit, so current only flows when making a test.

When current is flowing, there is a certain absolute potential at 1 and a lower potential at 3 in order that current should flow in that direction; and there is also a certain potential at 2 and a certain potential at 4. In order that there may be no *difference of potential* between 2 and 4, the fall of potential from 1 to 2 must equal the fall in potential from 1 to 4, although the currents and resistances in these branches may be different. Similarly the fall in potential from 2 to 3 must be the same as from 4 to 3. In other words, by Ohm's law

$$C_aA = C_bB \text{ and } C_cC = C_xX.$$

When there is no difference of potential between 2 and 4 the current in A is the same as in C; and in B the same as in X, or

$$C_a = C_c \text{ and } C_b = C_x.$$

Therefore

$$C_aA = C_bB \text{ and } C_aC = C_bX$$

and dividing one by the other

$$\frac{A}{C} = \frac{B}{X} \text{ or } X = \frac{BC}{A}$$

from whence A, B and C being known, X is readily calculated.

If the resistances in the balance arms A and B are equal when a balance is obtained, then the unknown resistance X is equal to the resistance found in C. If B is greater than A, the resistance in C must be multiplied by the number of times B is greater than A, and similarly if smaller than A, divided by the number of times it is smaller.

Resistance Coils.—The resistance coils are usually made of German silver wire as that is effected very little in its resistance by a change of temperature. In order to prevent the effects of self-induction due to the current and of magneto electric induction due to magnets or soft iron in the neighborhood of the coils, it is necessary that the current be doubled back on itself. The wire should be either wound on the bight as in Fig. 169, or, if there are to be many turns, the first layer should be wound right handed and the next left handed and so on, each layer being secured so as not to unwind when the next layer is wound. Then again the bobbin on which the wire is wound may be divided into halves, the upper half being wound right handed and the lower left handed.

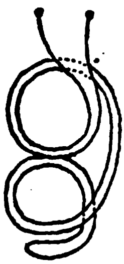


FIG. 169. Winding of Resistance Coils.

After the coils are wound they are dipped into melted paraffin, so on cooling every portion is covered, being protected mechanically and electrically.

The rheostat arm of the bridge may be used as a separate resistance, and if so used, care must be taken that too great current is not sent through coils, as they are delicate and liable to be burnt

out. The same precaution is necessary in using the galvanometer as a separate instrument, as the coils of that instrument cannot stand too heavy a current.

Silver Chloride Cell.—As has been stated this form of cell is ordinarily used in testing sets, and in order to use the set intelligently a short description of it is given. The positive electrode is a zinc rod and the negative electrode consists of a silver rod surrounded by silver chloride melted into a cylinder upon the rod. The electrolyte is sal ammoniac, but in the dry cell, as used with testing sets, the water is replaced by some gelatinous substance which differs in its composition according to the maker, it generally being a paste containing zinc oxide, zinc chloride, sal ammoniac, lime and water.

When the cell generates current the chlorine in the ammonium chloride (sal ammoniac) is displaced by the zinc and the ammonium set free displaces the chlorine in the silver chloride, leaving metallic silver deposited on the silver electrode. There will be no free gas given off unless the cell is worked too hard. This cell gives under ordinary conditions about 1.1 volts.

Galvanometer.—The form of galvanometer used with most testing sets consists of many turns of fine silk-covered wire wound on a single bobbin. The needle is pivoted and lies exactly in the center of the coil and is entirely covered by it. The needle carries a pointer at right angles to it and passes over a scale on which divisions are marked. The needle is provided with a lever for lifting it clear of its pivot when not in use, and is controlled by a separate magnet to enable it to be used in any position, the pointer showing zero on the scale when no current is flowing.

These galvanometers are made to be very sensitive, a current of one-twentieth of an ampere giving a deflection of 25 degrees. This is effected by the great length of wire used on the bobbin, the nearness of the wire to the needle and the delicate pivoting of the needle.

Service Testing Set.

One form of Wheatstone bridge furnished to ships is that made by Queen & Co., called the Queen-Acme Portable Testing Set.

The bridge, battery and galvanometer are all placed in a compact box of seasoned mahogany fitted with lock and key.

The upper face of the set is shown in Fig. 170, the full lines and circles showing the connections, binding posts, keys and terminals on the outside of the box and the dotted and broken lines the connections under the face which is of hard rubber.

The Coils.—The coils are wound of platinoid wire carefully seasoned to prevent gradual changing of the resistance with time. The wire has a low temperature coefficient and the endeavor is to have corresponding coefficients for all the coils. The rheostat coils are adjusted to an accuracy of $\frac{1}{8}$ of one per cent and the bridge coils

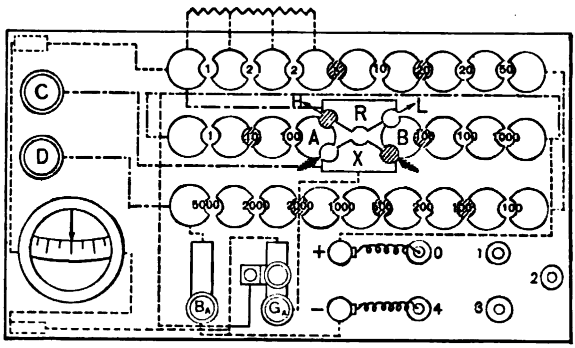


FIG. 170.—Queen-Acme Testing Set

to an accuracy of $\frac{1}{10}$ of one per cent. The rheostat coils are sixteen in number, their combined resistance being 11,110 ohms. In each bridge arm there are three coils of 1, 10, 100 ohms and 10, 100, 1000 ohms respectively. The commutator admits of a ratio of 1 to 1000 on either bridge arm, and the theoretical range is from .001 to 11,110,000 ohms, though for resistances above 1,000,000 ohms additional battery power is required.

The Galvanometer.—This of the d'Arsonval type. The current from the battery flows in a conductor wound around an iron core on which the needle is pivoted, and this coil and core revolves between the poles of a permanent magnet which produces an intense permanent magnetic field. When current flows around the coil another magnetic field is set up, and the coil carrying the needle

takes a position due to the resultant forces of the permanent and the temporary fields.

The Battery.—This consists of four special dry cells, one or more of which may be used as desired. They maintain a steady E. M. F. and are good until exhausted. The cells have a very low resistance and will last for months with care even though the set may have daily use.

The Keys.—There are two single contact keys. The left-hand key is a single contact key in the battery circuit. The right-hand one is in the galvanometer circuit and is a short-circuit key. When depressed it closes the galvanometer circuit and when released it short circuits the galvanometer, bringing it immediately to rest.

Connections and Circuits.—The connection and circuits are readily understood by referring to Fig. 315. The top row of blocks is connected to the bottom row by a heavy copper bar joining the right-hand blocks. These two rows together constitute the rheostat. Any resistance from 1 to 11,110 ohms may be obtained in this rheostat by removing the proper plugs. The lower left-hand block of the rheostat is connected to the lower line post *D*. The upper line post *C* is connected to block *X*. This block *X* has no other permanent connection excepting that it is joined to one end of the galvanometer key. The block *R* is connected to the upper left-hand block of the rheostat and otherwise has no connection excepting by plugs. The end blocks of the middle row are connected by a heavy copper bar. Each half of this row constitutes a bridge arm, designated *A* and *B* respectively. Starting from the lower line post *D*, the circuit is continuous from there through the rheostat and then through first one bridge arm and then the other back to the other line post *C*.

The function of the commutator is to transpose the two bridge arms *A* and *B* so that they are passed through in reverse order. All of the above connections are in circuit with the resistance being measured and are made sufficiently heavy to add no appreciable resistance to the circuit.

The two battery terminals + and — are connected, one directly to the common junction of the two bridge arms, the other through the battery key to the rheostat.

The two galvanometer terminals are connected, one directly to the block *R,* while the other connects through the galvanometer key to the block *X*. The blocks *A, B, R* and *X* are joined by plugs as shown by the shaded circles between the blocks.

The Commutator.—This consists of the blocks *A, B, R* and *X* and two plugs. When these two plugs are in the position shown in the figure, the bridge arm *A* is connected to the rheostat and the bridge arm *B* to the line. In this position the following relation holds

$$\frac{A}{B} = \frac{R}{X}$$

and the bridge is in a position for measuring high resistances, indicated by the arrow marked *H*.

If the plugs have the opposite position, the bridge arms are reversed, the one that was connected to the rheostat now being connected to the line, and the one to the line being joined to the rheostat. In this position, the following relation holds

$$\frac{A}{B} = \frac{X}{R}$$

and the bridge is in a position for measuring low resistances, indicated by the arrow marked *L*.

Uses of the Set.—This testing set may be used to measure *resistances, either high or low, insulation resistance, to compare E. M. F. of batteries, to check a voltmeter, to measure battery resistances, to check an ammeter* and to make what is known as the *Varley Loop Test.* These will be described in Chapter XXX.

Magneto.

This is an instrument used in testing electrical circuits and in a limited degree for measuring resistances. It can be used to detect an open circuit, to detect a ground or to locate a fault in an open circuit, and within limits to measure resistance.

In its most common form, it consists of two parts, a small dynamo or generator and a bell. The connections are shown in Fig. 171.

The field of the generator is furnished by two or more permanent steel magnets. Between the poles is rotated a small closed

armature, usually a simple rectangular coil wound on an iron core. There is a small crank on the outside of the case containing the generator to which is attached a toothed wheel which engages a smaller wheel connected directly on the armature shaft, so one revolution of the crank gives a great many to the armature. Connected in series with the armature is the bell circuit, and when connected for testing an outside circuit, that circuit is also in series with the armature and bell circuit. Current from the armature is led around an electromagnet, between the legs of which and on the end opposite the yoke, is pivoted an iron armature. This armature has secured to it at right angles an arm terminating in a striker for the bell. This striker projects through the case, and has motion between two bells, striking them alternately as it vibrates.

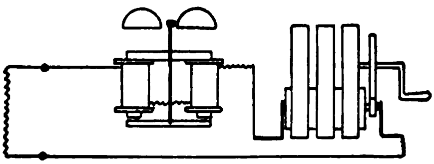


FIG. 171.—Magneto.

When the armature is revolved and the armature turned in the field of the permanent magnets, alternating currents are induced in the armature circuit and this being in series with the electromagnet causes alternating currents which cause an alternating change of polarity, causing the armature to be attracted first to one leg and then the other. This causes the striker to vibrate and a ringing of the bell is the result. This can only happen, however, when the armature circuit is complete through some outside circuit.

The E. M. F. produced in the armature depends to a great extent on the speed with which it is turned, but a good magneto should develop from 50 to 100 volts. For certain purposes, as will be illustrated later, it is necessary to know the maximum resistances that current can be forced through, and these data are usually stamped on them, varying from 3000 to 30,000 ohms.

Ohmmeter.

This instrument as its name signifies is one for measuring resistance, the value of the measured quantity being read directly in ohms from the scale of the instrument. In testing for faults or testing the goodness of the insulation used in an electric light installation, it is necessary that an E. M. F. at least as great as that under which the plant is to work, should be used. Such a high E. M. F. would be too great for use with the ordinary Wheatstone bridge testing set, so the ohmmeter is designed to be used with a small magneto giving the desired E. M. F., when the resistance can be read directly from the instrument. This instrument is of particular value in measuring insulation resistance, affording the most ready and rapid means of measuring it, its practical application being shown later.

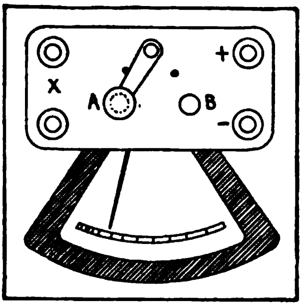


FIG. 172.—Ohmmeter.

Fig. 172 shows the general outside appearance of an ordinary ohmmeter. The two right-hand terminals are for the leading wires from the source of supply (generally a small magneto machine). They are marked + and —. The two left-hand terminals are for the leading wires to the unknown resistance to be measured. There are two contacts in the middle marked *A* and *B*, corresponding to the two scales on the face. If the switch is on *A*, the outer scale is to be used, and if on *B*, the inner scale.

Fig. 173 shows the interior construction, being a half section through the coils viewed from underneath. There are three coils, the two outer ones, *a, a*, being placed with their planes parallel and the coils connected in series; the third, *b*, being placed between them with its plane and magnetic axis at right angles to those of *a, a*. There is a small steel needle pivoted in the center of the coil *b* with its magnetic axis lying in the common axis of *a, a*. To this needle is attached the pointer and the coil *b* is so cut away as to allow a wide range for the travel of the pointer. Underneath the pivoted needle is a small weak bar magnet to counteract the earth's magnetism, so the needle only acts under the influence of the coils when current flows through them.

Any current flowing through *a, a,* tends to keep the needle in its zero position with its length in the common axis of *a, a.* In this position the needle is parallel to the plane of *b* and any current through *b* tends to deflect it, and the needle will take a position depending on the relative strength of the current in the coils.

The coils *a, a,* of high resistance are connected only to the source of E. M. F., but the coil *b* which is connected to the same source of E. M. F. is also connected in series to the high resistance to be measured. The current through the deflecting coil *b* is inversely proportional to the resistance and directly proportional to the E. M. F., while the current through the magnetizing coils *a, a,* is directly proportional to the same E. M. F. Any variation of the E. M. F. affects equally both the magnetizing and deflecting currents, so the deflection of the needle is simply inversely proportional to the resistance to be measured, the resistance of *b* being small.

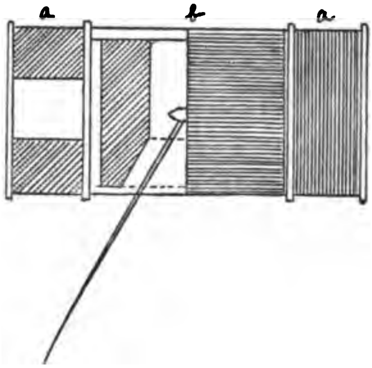


FIG. 173.—Coils of Ohmmeter.

If the resistance to be measured is infinite no current flows through *b* and there is no deflection of the needle. As soon as the resistance is at all lowered a certain small current flows producing a small deflection, and by simple calibration the scale can be marked to indicate directly in ohms the value of the unknown resistance.

The Evershed Testing Set.

The ohmmeter described in the preceding section is known as the Evershed ohmmeter, but a later form of this instrument is now made, known as the Evershed Testing Set. This instrument is made by Queen & Co., and the description and use of this instrument has been furnished by the makers.

The electrical principle involved is the same as in the case of the ohmmeter, but the arrangement of the coils is slightly differ-

ent. This is shown in Fig. 174. The leads from the magneto are secured to the terminals marked A (+), B (—), and the unknown resistance to terminals C and D, one of which is marked "Earth" and the other "Line." For testing insulation the conductor under test is connected to the earth terminal, and the other terminal is grounded.

Inside the terminals A and B, the current divides, part flowing through the coil P, called the pressure coil, through a constant resistance R, and part through the unknown resistance and through

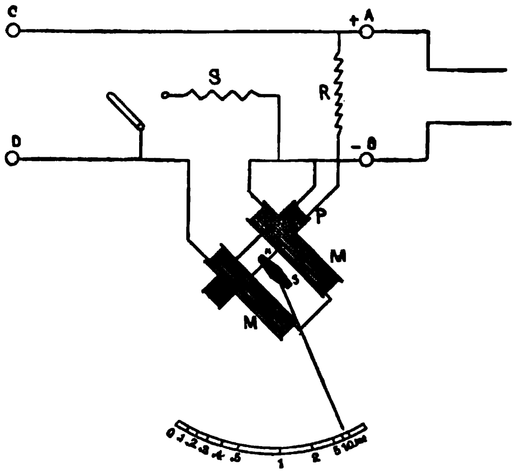


FIG. 174.—Connections of Evershed Testing Set.

the coils MM in series, these coils being known as the current coils. The action of the pressure coil is to keep the axis of the needle NS perpendicular to its own coil and that of the current coils to deflect the needle. This needle carries the pointer travelling over a graduated scale from points marked 0 to infinity.

When there is no leakage on the line, there is no current through MM and consequently the needle remains at rest, with the pointer indicating infinity, showing an infinite resistance on the line. When the line resistance is so low as to be negligible, the current flowing through the current coils depends on the voltage and the

resistance of the coils, and the needle will be deflected to a position in which the turning moments of the two coils P and MM are balanced. This point on the scale is marked 0 and for any given resistance in the line the pointer will come to rest at a point between 0 and infinity. The position of the pointer will not be changed by altering the voltage of the magneto, for the currents in the coils will be increased or decreased together, so their ratio remains unchanged.

The scale is marked in tenths and units of megohms, thus indicating directly the resistance measured.

Magneto.—In the latest pattern of this testing set, the magneto is built after the fashion of a modern continuous-current generator. It has a tunnel-wound armature with a finely laminated core built from stampings of best iron of "transformer" quality, a special form of commutator with elastic roller brushes and roller bearings for the armature axle. The armature is driven by double gearing by a winch handle so hinged that it may be turned into a recess in the box when not in use. A flexible double conductor connects the magneto to the ohmmeter.

Needle.—The ohmmeter has a very finely pivoted astatic needle system, magnetized by the magneto current. The needle system is automatically lifted off the jewel bearing and clamped by the action of shutting the lid of the box. The current coils MM are wound with an enormous number of turns of the finest wire so as to secure the maximum sensibility. A one-ninth shunt S is provided so as to reduce the sensibility ten times when low insulation resistances are being tested.

Instructions for Use.—Adjust the ohmmeter until the bubble is in the center of the spirit level.

Place the generator not less than 18 inches away from the ohmmeter and couple its terminals to the marked terminals on the ohmmeter.

Couple the mains to be tested to the *line* and *earth* terminals of the ohmmeter. Turn the generator handle steadily in either direction at any speed above 60 revolutions per minute and the ohmmeter index will point to the resistance under test.

The Evershed Megger.

A megger is a name applied to an instrument for measuring very high resistances, the indicating scale being marked in megohms. The Evershed Megger is a modified form of the Evershed Testing Set previously described. It differs from it in that the testing set is constructed on the principle of the reaction exerted between current carried in *stationary coils* and a *movable magnet* while the

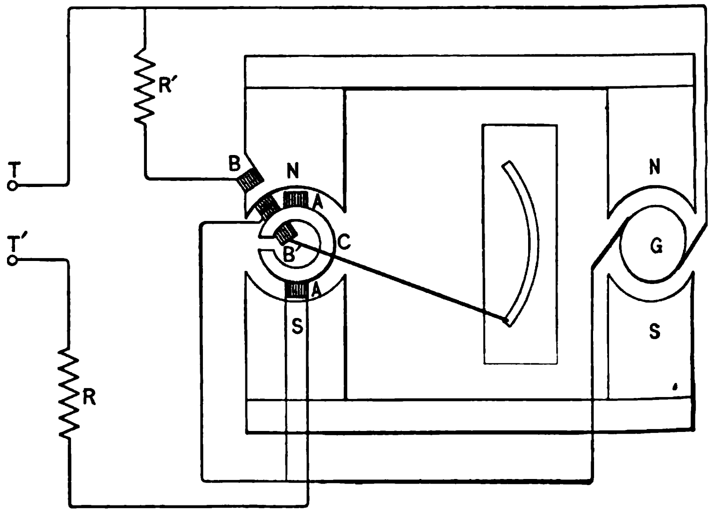


FIG. 175.—Electrical and Magnetic Circuits of Megger.

megger is of the d'Arsonval type of instruments and is constructed on the principle of the reaction exerted between current carried in *moving coils* and a *stationary magnet.*

The operating features are contained in one case and the power is obtained from a hand-driven magneto. This is made in different sizes and E. M. F.'s of 100, 250, 500 or 1000 volts may be generated for 100 R. P. M. of the crank. The coils are separately connected to commutators of a peculiar disc form and against these spring disc brushes roll, making light but sure contact.

The electrical and magnetic circuits are shown in Fig. 175.

N and S represent the *permanent* magnets of the system. Between one set of poles, the armature G is revolved by the hand crank. Between the other set of poles is secured a C-shaped iron piece C, in order to produce a uniform field for the region in which the pivoted coils move. This gathers up the lines of force due to the pole pieces and causes the flux to be very evenly distributed between it and the pole faces.

There are two sets of moving coils, the *current* coil A and the *pressure* coil B^1, with an auxiliary coil B in the same plane as B and secured to it. All these three coils are rigidly connected together and B^1 carries the pointer which moves over the graduated scale.

These coils are shown as they appear looking down on them and they all are suspended together on vertical pivots at the top and bottom over and under the center of the C-shaped piece. Their terminals are brought to slender copper strips which press lightly against circular rings on the vertical shaft to which the current leads are secured. Coils B and B^1, called the pressure coils, are connected in series and directly across the generator leads in series with a resistance R^1. Coil A, called the current coil, is in series with the resistance to be measured through a resistance R.

When the terminals T and T^1 are not closed and the armature is turned, current flows through coils B and B^1 and they would take a position at right angles to the direction of the magnetic flux, which would be opposite the gap in the C-shaped piece, and as all the coils are connected, A would be carried with them, A at this time having no current. In this position the pointer would be at the other end of the scale from that shown and would indicate infinity. If a resistance is connected to the terminals and the crank turned, the E. M. F. would cause current to flow through A and the resistance. The current is so led through A that it would be urged to a limiting position at right angles to the flux, but in tending to assume this position it would move in the opposite direction to that in which B^1 moved, as the current is led to it in an opposite sense. Its limiting position fixed by mechanical considerations is that shown in the figure. The same E. M. F. urges B and B^1 in

one direction and A in the opposite direction, and B and B^1 exert a stronger and stronger restraining torque as A moves. The coil of B is so wound that the polarity of its face nearest the pole of the permanent magnet is the same as that of the pole, which acts as a restraining force acting against the movement of A. The resistance connected to the terminals, in conjunction with the E. M. F., determines the amount of current through A, and consequently the distance the system of coils move and the distance the pointer is carried. If the terminals are short circuited, the excess of current in A will cause it to take its limiting position which would be marked zero on the scale.

Any change in E. M. F. due to difference of R. P. M. of the armature affects the currents in all coils alike and the resulting difference of torque between the coils is always the same for the same resistance and the pointer will remain steady.

One terminal is marked "line" and the other "earth." To measure the insulation resistance of a conductor to ground, it is only necessary to connect the conductor to the terminal marked "line" and the other terminal to "ground." On rapidly turning the armature the resistance will be indicated by the pointer.

Potentiometer.

A potentiometer is an instrument by means of which voltages are measured in comparison with a standard cell, or by which E. M. F.'s of cells are compared with one another. It can also be used for accurate measurements of currents, voltages and resistances and for the calibration of measuring instruments. With it, voltages a fraction of a millivolt to several thousand volts can be accurately compared with the E. M. F. of a standard cell, and currents ranging from a small fraction of an ampere to many thousand amperes may be measured.

The principle of the potentiometer is illustrated in Fig. 176.

CD is a uniform conductor of such size that its resistance will not be materially changed by the heat which is produced by the current flowing in it. It is shown as being divided into 16 equal parts, 15 to the left of the point marked 0 and 1 to the right. It is

immaterial what the resistance of each of these parts may be, but it is absolutely essential for accurate measurements that the resistances of all parts be equal. The ends of this wire are connected to the terminals of a battery B and in series is joined a regulating rheostat R. The battery should preferably be a storage cell or one that gives a continuous steady current.

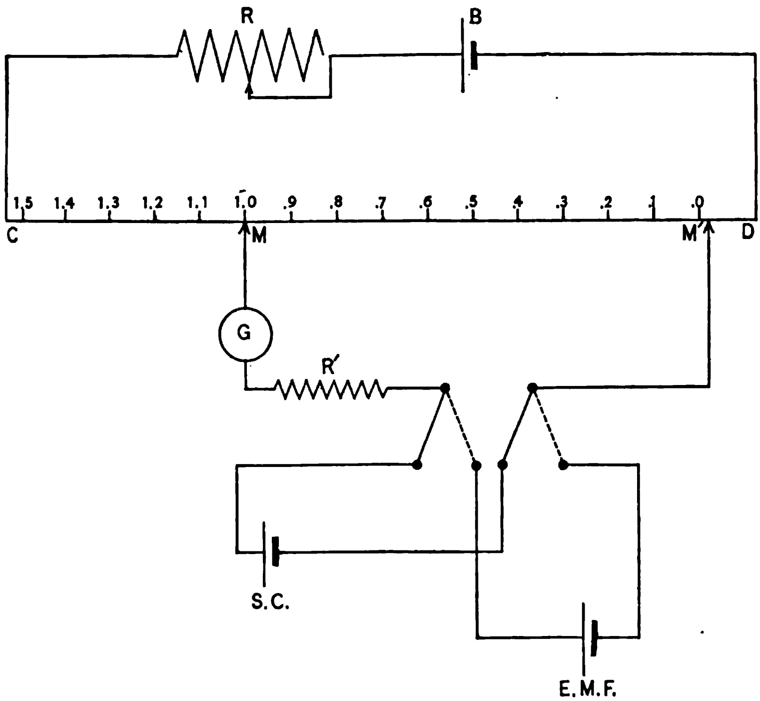


FIG. 176.—Connections of Potentiometer.

Assuming that each portion of the wire is of 5 ohms resistance, and neglecting for the present the connections at M and M^1, the potential difference at the end of the wire CD is $C(16 \times 5) = 80C$. Assuming that this potential difference is 1.6 volts, the current flowing through it would be $1.6 \div 80 = 1/50$ of an ampere. The drop of potential between the terminals of any one of the 16 equal parts would be $1/50 \times 5 = 1/10$ volt, and over the whole

wire $1/50 \times 80 = 1.6$ volts. The equal parts of resistances can then be marked to represent volts as shown in the figure by the numbers .1, .2, .3, etc. The part to the right of the *O* is divided into tenths, so the drop across each of these parts is .01 volt. By dividing this portion still more minutely, the potential drop can be measured to thousandths or ten thousandths, depending upon the accuracy with which this portion of the resistance can be divided.

Connected at M and M^1 to the resistance wire is a circuit which contains a galvanometer G, a protecting resistance R^1 and through the double throw switch a standard cell SC, which should be so

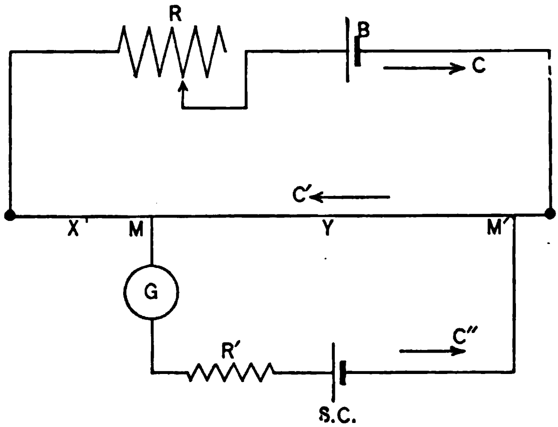


FIG. 177.—Elementary Connections of Potentiometer.

connected that its current opposes that of B. This is diagrammatically shown in Fig. 177.

Calling $E =$ E. M. F. of cell B,

$e =$ E. M. F. of cell SC,

$X =$ resistance to left of M,

$Y =$ resistance between M and M^1,

$R'' =$ all resistances in B's circuit except Y,

$R''' =$ all resistances in SC's circuit except Y,

and the currents as indicated, we have

$$E = CR'' + C'Y,$$
$$e = C''R''' + C'Y.$$

When M and M^1 have such positions that the galvanometer shows no deflection, $C'' = O$ and $C' = C$, or

$$e = CY. \tag{a}$$

Similarly if another cell is substituted for SC another position of M and M^1 can be found that will give no galvanometer deflection, and similarly

$$e^1 = CY^1$$

or

$$\frac{e}{e^1} = \frac{Y}{Y^1}.$$

Y and Y^1 are known and the E. M. F.'s of the two cells can be compared, and if the value of one is known, the other readily follows.

Suppose 1/50 of an ampere was flowing through CD, Fig. 176, when M and M^1 are connected as there shown, and no deflection of the galvanometer took place, then 1/50 of an ampere would also be flowing in the portion between M and M^1 and the drop of potential between those points would be $1/50(1.0 \times 5) + 1/50(.2 \times 5) = 1.02$ volts. Conversely if the terminal M was set at 1 and M^1 at .02, and R *regulated until no deflection occurred*, it is evident that 1/50 of an ampere was flowing and the voltage of SC must be 1.02 volts. This then indicates the manner by which the current of 1/50 is assured. If the E. M. F. of the standard cell is 1.02 volts, it is only necessary to set M and M^1 at their proper values on the resistance and regulate R until no deflection in the galvanometer takes place. When this is the case, substituting in equation (a) the known values of e and Y, a balance having been established, we have

$$1.02 = C(10 \times 5 + .2 \times 5) = 51C,$$

or

$$C = 1/50.$$

To measure the E. M. F. of another cell, it is now only necessary to throw the switch so as to connect the cell in circuit with the galvanometer, and *without changing the resistance in R*, so move M and M^1 that a balance is again obtained. Suppose when this took place M was at 1.2 and M^1 at .03, then the fall of potential between them would be $1/50(12 \times 5 + .3 \times 5) = 1/50 \times 61.5 = 1.23$

volts, or the E. M. F. could be read directly from the positions of M and M^1, 1.2 for M and .03 for M^1.

It is evident that the E. M. F. of B must be of such a value that the potential drop between C and D will be greater than the E. M. F. of the standard cell or of the cells to be compared.

The function of R^1 is to protect the galvanometer from excessive current when far from the balancing position and to prevent the standard cell from becoming polarized. As the balancing position is approached the resistance should be cut out in order to make the galvanometer more sensitive.

In actual construction, the resistance units are made up in a dial form, over which moves a sliding contact, so that M may be readily placed in any position. The part to the right of O has the same resistance as any one of the other portions, and in order that it may be divided into minute divisions, it is made very long and of very small diameter. By making it in the form of a spiral of ten turns of sufficient diameter it is readily divided into tenths, and by a sliding contact each tenth can be so divided that the potential drop can be read to ten thousandths.

Standard Portable Testing Set.

The testing set that has been adopted as the standard for ship board use consists in general of a Wheatstone bridge, rheostat, galvanometer, battery and keys, all properly arranged in a hard-wood carrying case. The theoretical range of the instrument is from .001 ohm to 10 megohms. The rheostat is arranged on the *decade* plan, and consists of the proper number of coils to permit a range of from 1 to at least 9999 ohms in steps of 1 ohm. The terminals of the coils are labeled in a manner permitting the value of the resistance coil to be readily determined, and each row marked for denomination, *i. e.,* for units, tens, hundreds and thousands.

The ratio coils are arranged on the plug-in plan.

Blocks are provided so that connections can be quickly made for locating faults by both Murray and Varley loop tests.

The galvanometer is of the d'Arsonval type and approximately dead beat, with an adjustment lever for the needle, so that it can be adjusted to the center of the scale and indicate zero.

HOPKINS ELECTRIC TACHOMETERS.

Principle of Operation.

The Hopkins Electric Tachometer consists of a small direct-current magneto generator and an indicating electrical voltmeter of the highest grade obtainable. The two parts of the system are connected by a duplex (two-wire) insulated cable. It is a well-known fact that when a system of coils is rotated within a permanent magnetic field an electric voltage or potential is generated in direct proportion to the speed of rotation of the moving coils. It is therefore possible to calibrate the electrical voltmeter in terms of speed; in this instance revolutions per minute.

This tachometer is furnished in two general types, portable and stationary.

The instrument may be one of the many well-known forms, that is a portable instrument for laboratory and general speed indicating service, or it may be of the switchboard type for mounting upon a wall or switchboard, or it may be in the form of a special waterproof cast brass case with an adjustable bracket for mounting on the dashboard of a motor car or the bulkhead of a motor boat.

The magneto can be arranged for portable service for attachment at will to the center of any revolving shaft, or it may be arranged with a base for stationary service for mounting in close proximity to any shaft, and to be gear driven, belted or direct connected to the shaft.

Description of Instrument.

The d'Arsonval or permanent field type of electrical instrument consists of a permanent horseshoe magnet between whose poles swings, in an arc of 90°, an extremely light moving system. This moving coil, which is mounted upon an aluminum frame, is supported by two unusually large and ruggedly constructed sapphire bearings.

Due to the principle of the d'Arsonval electrical instrument, the moving system is responsive to the most minute electrical pressures, from zero to the maximum angle of deflection. It also gives an angular deflection directly proportional to the electrical pressure

applied. In other words if the electrical pressure (voltage) is doubled the angular deflection of the moving system is also doubled. This means that an absolutely accurate and evenly divided scale can be, and is used on this tachometer.

There is nothing about this instrument to get out of order. There is no mechanical wear on it; there are no joints or parts to wear and cause lost motion; the accuracy of the system is unaffected by changes in temperature, and furthermore by using the permanent magnet type of instrument the tachometer gives absolutely steady readings at all speeds.

Construction of Instrument.

A phantom view of the instrument used with Model MB, Hopkins Electric Tachometer, is shown in Fig. 178. All instruments used are of this same principle and general construction.

The system is composed of a massive permanent tungsten steel magnet *B* carrying the pole pieces *C*, between which the moving element *F* turns, mounted in the sapphire bearings *H* above and below.

This moving element is lighter than the indicating movement of any tachometer made. It consists of an aluminum frame pivoted and carrying a light electrical winding and an aluminum pointer or indicating hand *N*. The scale plate, *M*, shown in the illustration as transparent, in this type of tachometer, is a silvered etched dial having uniform graduations throughout its entire length.

The small spool *L* carries a very fine resistance wire of zero temperature coefficient, which is the means of securing refinement and permanence of calibration.

A separable junction box, shown at *I*, which screws into the back of the instrument, enables a user, even without knowledge of electrical connections, to install the instrument with facility. The wires *K* which lead from the magneto generator are enclosed in a waterproof brass armor *O*; this construction is used on all stationary type tachometers.

The entire instrument mechanism is enclosed in a beautiful pol-

ished brass waterproof case *A*, having a full, heavy, beveled plate-glass front. This type of instrument is attached to its support through the adjustable bracket and the instrument is adjustable to any convenient angle.

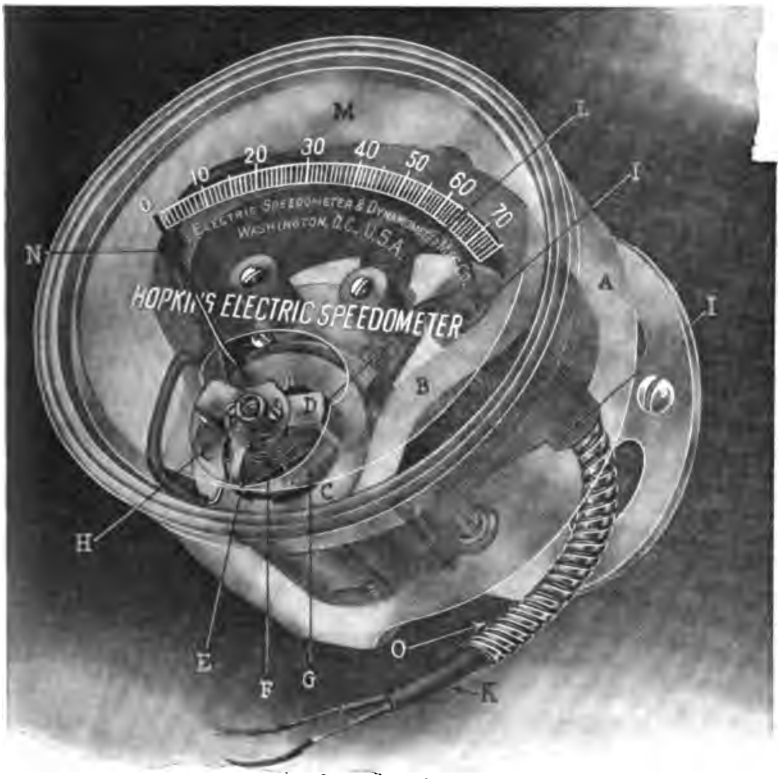


FIG. 178.—Internal Construction of d'Arsonval Electrical Voltmeter used with Hopkins Electric Tachometer.

Description of Hopkins Magneto.

The Hopkins magneto is of the direct current type. It consists of a three-coil armature rotating between the poles of a permanent horseshoe magnet. The current generated in the armature is sent to the line through a commutator of three parts; the rotating bars

being of pure platinum and the brushes or contactors of 20-karat gold.

Because of the use of gold brushes and platinum commutator bars no variation in the resistance of the circuit occurs, as there are no oxidation changes nor insulating salts formed. This fact makes it possible to construct and guarantee an electric tachometer of permanent calibration.

The magneto armature is gear driven from the main or external shaft by spur gears that are made with great care in order to obtain a perfect running pair. This unique design brings the bearings of the armature and commutator entirely within the water-tight and dust-proof case where grit cannot grind them away. This construction also allows of a *very small air gap,* around the armature, between the magnet limbs, thereby insuring permanence of the thoroughly aged magnet. Because of these internal gears, any wear on the main bearings will not cause the armature to collide with the pole pieces, nor will any end play of the main driving shaft cause any trouble with the brushes on the commutator. Furthermore, any chatter set up in the main driving shaft is not communicated to the armature and commutator shaft, and therefore allows of a very steady reading tachometer.

Also by using internal reduction gears remarkably high speeds can be measured with precision *without exceeding* the practical bounds of commutation. In addition the internal reduction gears minimize the *commutator and brush wear.*

Construction of Magneto.

In Fig. 179 is shown a phantom view of the internal construction of the Hopkins magneto, which is a simple and effective design.

Here again is a massive tungsten steel magnet *A,* between the poles of which rotates the small armature *B,* the commutator of which is composed of three platinum bars *C,* and the brush gear, which consists of four small gold brushes *D,* acting upon the barrel of the commutator and held in position by the long flexible bronze springs *E.*

The driving of the armature is accomplished by internal gears, the pinion gear *G* on the main shaft, and the armature gear *F*. The wires *L* are led out through the flexible brass armor *K*

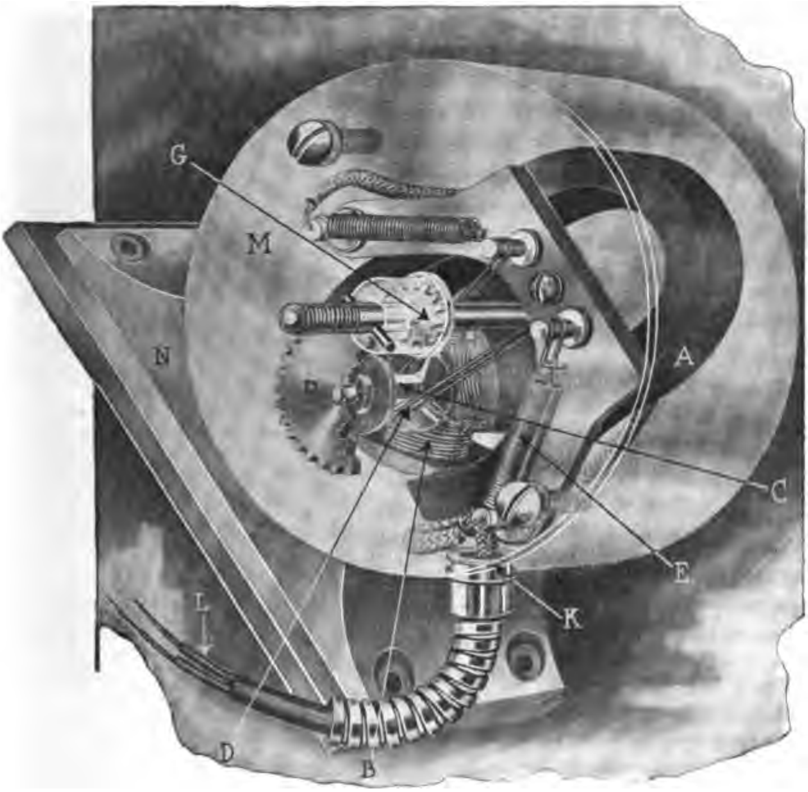


FIG. 179.—Internal Construction of Hopkins Magneto.

in the stationary type, while in the portable type they are connected within the containing case of the magneto to the binding posts.

The entire generating mechanism is enclosed in the cast phosphor bronze water-tight case *M*, having in the stationary type a base *N* for ready installation.

Model P—Portable Tachometer.

This instrument consists of the same high grade d'Arsonval voltmeter of the portable type and a portable magneto arranged with binding posts, a diamond-shaped point and a polished mahogany handle. The two parts of the tachometer, the indicating instrument and the magneto, are connected with a pair of flexible leads of sufficient length to allow the instrument to be placed upon a suitable table or stand near the shaft whose speed is being indicated.

The instrument used with the portable tachometer is of exactly the same type and principle as that shown in Fig. 178, except that it is mounted in a polished mahogany case having a large leather handle for easy transportation. The scale is fitted with a high-grade mirror and the indicating pointer is of the hair-line type moving above this mirror and scale so that precise indications can be observed, eliminating parallax errors.

The portable tachometer has in circuit a rheostat of wire of zero temperature coefficient, with a moving contact of non-oxidizing metal so that calibration can be adjusted at any time. This rheostat is operated by a suitable screw on the face of the instrument, as shown in Fig. 178. In double scale tachometers each scale has an independent rheostat.

In the portable magneto a ball thrust bearing is inserted in the main bearing next to the handle so that the magneto may be held against a revolving shaft with any degree of pressure without in any way injuring or impairing the operation of the magneto.

To recalibrate the tachometer at any time, check its indication upon a slow speed shaft and if possible upon one giving uniform rotation, with a revolution counter and stop watch and adjust the instrument for this speed with the rheostat for that particular scale. The tachometer will then read with precision accuracy throughout its entire range. To raise the reading turn the rheostat clockwise. To lower the reading turn the rheostat counter clockwise. If while the tachometer is being calibrated its indication is perfectly steady and uniform the shaft upon which it is being calibrated is revolving at an absolutely uniform rate.

Stationary Tachometers.

Stationary tachometers are furnished with a zero center scale and calibrated "ahead" and "astern" in order to indicate not only the speed of the propeller shaft in either direction, but to give information that signals from the bridge have been correctly received and executed.

The magneto is driven from the propeller shaft by a split gear which engages with the gear on the magneto shaft while indicators may be mounted on the bridge, in the conning tower, central station, engine-rooms or other desired stations.

This type has been installed on ship board to meet the demands of an engine revolution indicator, the pointer showing at all times the direction of revolution of the main shaft as well as the number of revolutions per minute being made.

Electric Fault Finder.

As the name implies, this is a device for locating faults in electric circuits, such as leaks, grounds, fractures, short circuits, open circuits, etc. It will perform all the functions of the magneto and has the advantage of requiring but one person to perform the tests. The vibrating bell of the magneto is replaced by a telephone receiver and the absence or presence of sound in it, or the relative intensity of sound is a measure of the state of leak or ground.

An inspection of the wiring diagram in Fig. 180 will show the connections of the fault finder as made by the Electric Controller and Supply Co. This shows an induction coil in which the primary is energized by four cells in parallel, in the circuit of which is a high frequency buzzer for making and breaking the circuit. The alternating currents induced in the secondary flow, by properly arranged switches, through a telephone receiver and the circuit under test. Thus it will be seen that, if the primary circuit is made and switch 1 is closed, the circuit through the receiver is only complete when there is some connection between the external terminals. With this combination, it is seen that the device will perform as an ordinary

magneto, sound being produced in the receiver when the external terminals are closed, and the relative intensity of the sound is a measure of the resistance between the terminals in the same manner that the loudness of sound of the bell in the magneto is a measure of the resistance.

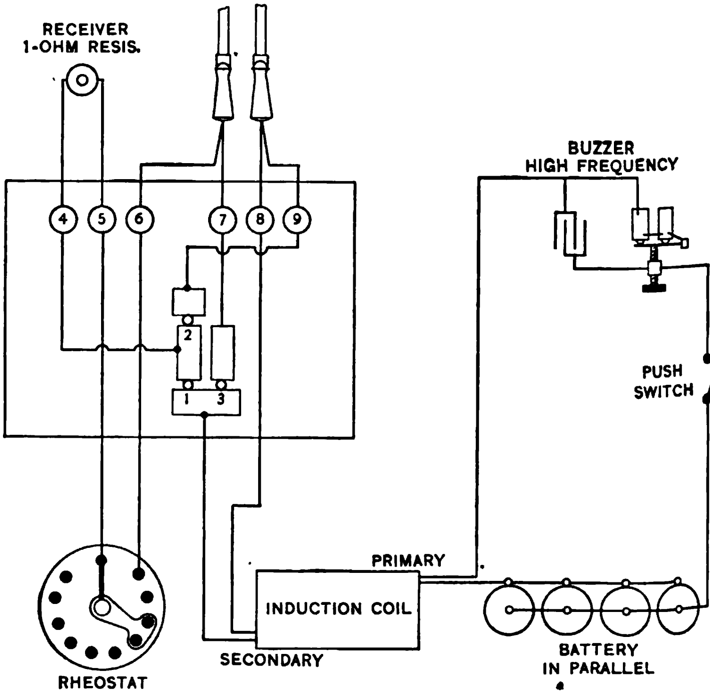


FIG. 180.—Wiring Connections of Electric Fault Finder.

Wattmeters.

A wattmeter is an instrument for measuring watts, or the electric power developed in a circuit. Power in a direct current circuit is equal to the product of the current delivered times the voltage at which it is supplied. This power may be obtained at any time by taking simultaneous readings of a voltmeter and ammeter connected in circuit and taking their product. A wattmeter so constructed as to show the product of instantaneous values of volts and amperes

is called an **indicating** wattmeter. One so constructed that will graphically record the product of volts and amperes is called a **recording** wattmeter. It is generally desired to know the power used during a certain interval of time, and an instrument that will allow the product of power times the time to be found is called a **watt-hour** meter. Another form of meter which measures the product of current alone and the time is called an **ampere-hour** meter.

Practically all watt-hour meters are of the motor type, a small motor being arranged to revolve at a speed proportional to the rate at which energy is passing through it. The number of revolutions of the motor may be recorded on a dial, and by calibration a constant may be found, which, when multiplied by the number of revolutions, will give the energy used in watt hours. The shaft of the motor which drives the indicating mechanism is generally geared to it in such a manner that the indications are read directly in kilowatt hours.

The current that passes through the motor armature may be taken from a circuit shunted from the main circuit, in which case it is proportional to the line voltage. The field may be energized by the line current, and the attraction between the field and armature currents, and hence the speed, is proportional to voltage times current, or proportional to the power flowing. Or, the main current may be led through the armature and the field energized by the line voltage, producing a similar effect, and the revolving armature may be geared to a counting mechanism that will allow the power to be read directly in kilowatt hours.

A type of wattmeter that has been installed on ships' switchboards is that known as the Sangamo meter, a description of which follows.

Sangamo Meter.

The principle of operation of the Sangamo meter is extremely simple, and depends upon the fundamental law of motors that current passed at right angles through a magnetic field is urged in a direction at right angles both to the current flow and the field. The motor element of the meter, as it is called, is shown in Fig. 181.

It consists of a molded insulation receptacle with a thin pressed metal bottom, held to the receptacle by means of a heavy brass clamping ring; the very shallow circular space between the inside of the receptacle and the metal bottom containing the armature. The armature consists of a thin copper disc and it is completely immersed

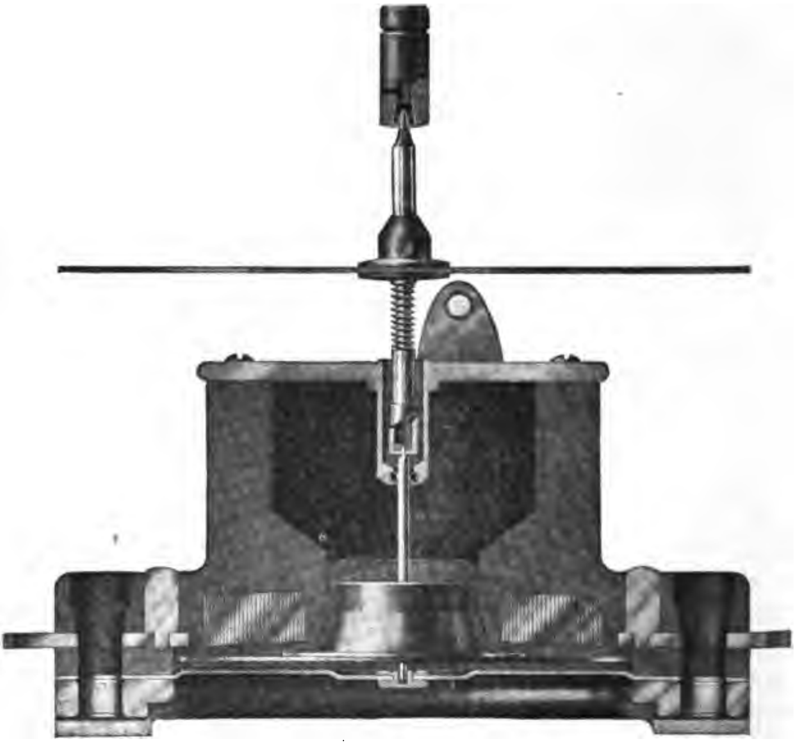


FIG. 181.—Cross Sectional View of Sangamo Meter.

in mercury which is plainly indicated in the figure. The current terminals, shown at each side to the right and left, are nickel-plated copper ears, which are deeply imbedded in the insulating material, and serve to lead current into and out from the mercury and the copper armature. Inside the molded insulation piece above the armature is shown as sectioned at two points a laminated steel ring. This acts as a part of the magnetic circuit for the magnetic

lines emanating from a U-shaped laminated steel yoke which is bolted to the brass ring, the poles coming just under the laminated steel ring. In the direct current type a pair of fine wire shunt coils is carried on the arms of the yoke and receives current from the line supply.

With the field energized by the line voltage and the line current flowing through the armature, the latter is urged in a direction at right angles to the field and revolves at a speed which is proportional to the torque, developed by the reaction between the armature and field currents. A damping effect is produced by the revolution of a disc carried by the operating spindle between the poles of permanent magnets.

FIG. 182.—Sangamo Switchboard Meter.

Secured to the armature by means of a disc and a float above it is the spindle which actuates the indicating mechanism, which is shown in Fig. 182, showing a switchboard wattmeter with a four-cycle integrating train.

In this type of meter, the armature *floats* in the mercury in which it is immersed, the necessary lifting effect for the weight of the entire moving system, including the armature, operating spindle, clamping disc, etc., being obtained by the small solid non-metallic float riveted to the center of the copper disc. The buoyancy is such that a very slight pressure is exerted in the jewel bearing at the top, thus rendering these meters absolutely proof against jars and shocks of severe service and reducing friction to a minimum.

The mercury chamber is designed somewhat like an inverted ink

well, so it is impossible to spill the mercury, no matter in what position the meter may be turned or placed.

Operation with Shunts.—The maximum rated full-load current through the armature of the direct current meter is 10 amperes, so that in capacities above 10 amperes the meter is operated from shunts, similar to an ammeter and its shunt, with the difference that the leads from the shunt terminals to the instrument must always be large enough to carry 10 amperes. Every Sangamo meter of whatever capacity is simply a 10-ampere meter properly adjusted for drop with respect to the shunt and with a recording train so

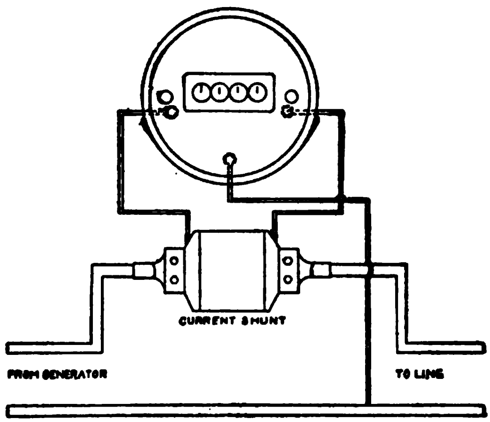


FIG. 183.

geared as to read directly in kilowatt hours for the actual total energy passed through the shunt and meter. If the meter is correct as a 10-ampere meter and is correct for drop through the cables and meter, the combination with the shunt must be right.

The method of connecting the Sangamo meter in circuit with a shunt is shown in Fig. 183.

Speed Adjustments.—The heavy load adjustment consists of a soft steel disc above the permanent damping magnets, shown in Fig. 182, arranged so that it can be screwed up or down to shunt more or less of the field of these magnets, varying the retarding effect and the speed of the motor as required without moving the magnets.

The light load adjustment consists of a small clamp on a pair of parallel wires at the bottom of the meter in front. The movement of this clamp to the left or right varies a small initial or starting current through the armature. This adjustment is of wide range, is easily obtained and absolutely positive.

In addition to the above adjustments, there is a sliding series adjustment for the purpose of setting a meter for correct resistance or drop, with respect to the shunt with which it is to be used. This adjustment is the small clamp just to the right of the laminated magnet. It is seldom that it is necessary to alter this adjustment unless the meter has suffered some accidental injury.

Light Load Compensation with Thermo Couple.—Behind the shunt coils is a thermo couple compensating device for light load; this being two strips of dissimilar metal joined together and surrounded by a heating winding of resistance wire in series with the shunt coils of the meter. The purpose of the thermo couple is to pass a low potential current through the armature in order to give a slight initial torque to overcome the unavoidable bearing friction, slight as this may be. The thermo couple is so arranged that the current set up in it will always pass from left to right through the armature chamber, no matter which way the heating current passes in the winding surrounding the couple. Thus it is necessary to connect the meter in circuit so that the load current will always flow through the armature in the same direction as the current set up by the thermo couple. This necessitates having the incoming terminal to the meter *positive* in order to get the correct light load compensating effect, for if current passes through the meter the other way, even though the shunt field is also reversed, giving proper direction on heavy load, the effect of the thermo couple will be in opposition, causing the meter to be very slow on light load.

Sangamo Ampere Hour Meters.

These meters are designed for use in circuits in which the power used is obtained from storage batteries, and as the name implies, the indicating mechanism registers in ampere hours. The operating mechanism is entirely similar to that described for the kilowatt hour meter, with the exception that the field is produced by per-

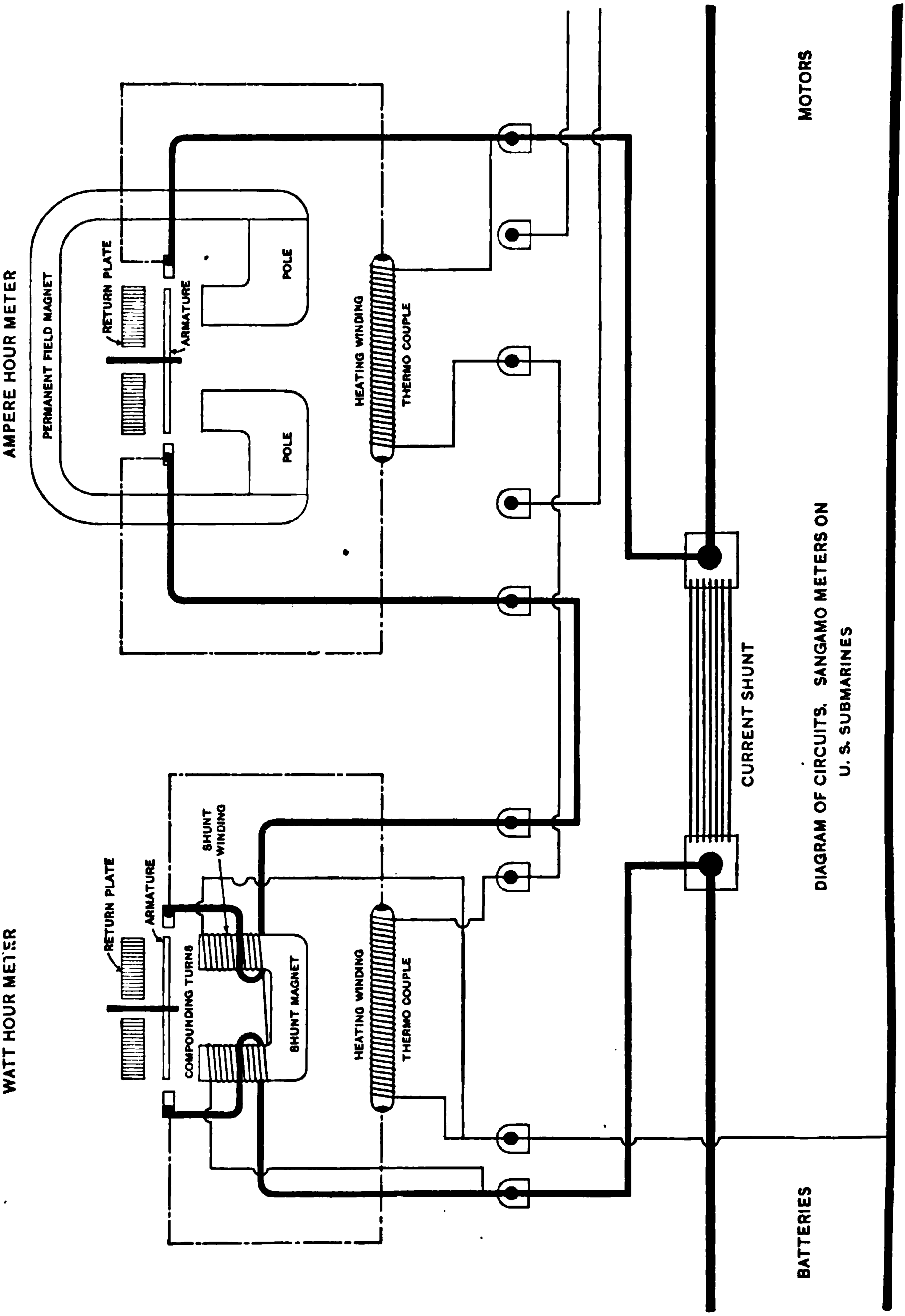


DIAGRAM OF CIRCUITS. SANGAMO METERS ON U. S. SUBMARINES

Fig. 184.

manent magnets, making the motor speed independent of the line voltage, as voltage is not a factor entering into the quantity to be indicated. The indicating mechanism, driven by the armature is such that the number of ampere hours is directly read off from one circular dial.

As used on the switchboards of submarine vessels using storage batteries as their propelling power, Sangamo meters are designed for the control of the cycles of charge and discharge. The equipment of submarines consists of two meters for the forward battery and two for the after battery. One of these is a watt hour meter equipped with a duplex train, having two rows of circles. One row records the charge and the other the discharge, proper arrangements being made by detents in the wheel train to prevent the charge wheels from moving on discharge and vice versa. The other meter is in series with the watt hour meter and is a standard circular dial ampere hour meter. Both of these meters operate with a single shunt of 1800 amperes capacity. These meters have the special feature of thermo couple compensation which acts on discharge only. The charging of the batteries is done at a practically constant voltage and current value, but on discharge, both current and voltage values vary greatly and the meters are so arranged that they are able to stand the large discharge rates while underway and will also register with a fair degree of accuracy in port when the propelling power is off.

A diagram of the circuits of Sangamo meters as installed on submarine vessels is shown in Fig. 184. With the aid of the description given above, the connections should be easily traced and understood.

CHAPTER XXI.

MEASUREMENTS.

The measurements to be given are only those that can be made with the instruments described in the preceding chapter, viz.: the voltmeter, ammeter, testing set, magneto and ohmmeter. In addition to the above, a few standard resistances may be necessary, but they can usually be found on board ship, as, for instance, the rheostat arm of the testing set when small currents are used, or the "ampere shunt" resistance used with the ammeter when large currents are used.

To Measure Current.

Current is measured by connecting an ammeter directly in the circuit through which the current is passing.

To Measure Current without Opening the Circuit.—This can be done where there is a convenient switch in the line, for the ammeter may be connected around the switch, and the switch then opened, when the full current will pass through the ammeter.

To Measure Current by Resistance and Voltmeter.

By Ohm's law the fall of potential through a conductor equals the product of its resistance and the current then flowing. By knowing the resistance and measuring the difference of potential between its ends, the current is at once obtained. Fig. 185 shows how the connection should be made.

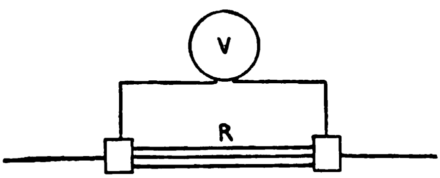


FIG. 185.—Connections for Measuring Current with Resistance and Voltmeter.

R is the standard resistance and *V* the voltmeter, which in this case should be a low-reading one.

To Measure E. M. F.

E. M. F. is measured by connecting a voltmeter to the two points between which the difference of potential is required.

To Measure Resistances.

High resistance may be measured by a voltmeter, by the testing set or by an ohmmeter.

Low resistance may be measured by an ammeter and voltmeter, or by a voltmeter and standard resistance.

To Measure Resistance with Voltmeter.—To do this requires a voltmeter of known resistance and a source of constant potential, as a running generator. The difference of potential across the mains of the generator is first measured and then the resistance to be measured is connected in series with the voltmeter, and the fall of potential through these two is measured across the mains whose difference of potential is constant. This is represented in Fig. 186.

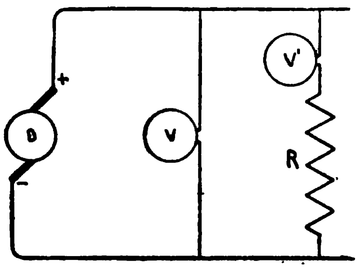


FIG. 186.—Connections for Measuring Resistance with Voltmeter.

Suppose V is the reading of the voltmeter when connected directly across the mains and V' the reading when it is connected up with R, the unknown resistance in series with it. Let X be the resistance of the voltmeter and C the current through V' and R, then by Ohm's law $V = C\ (X + R)$ and $V - V' = CR$.

Subtracting one from the other,

$$V' = CX \text{ or } C = \frac{V'}{X},$$

also

$$C = \frac{V - V'}{R}.$$

$$\therefore \qquad R = \frac{(V - V') \times X}{V'},$$

all of which quantities are known.

This method is available for high resistances and is particularly adapted for measuring insulation resistance as described farther on.

To Measure Resistance of a Voltmeter.—This is just the converse of the above, requiring a source of constant potential and a high resistance. The connections and readings are made as before, when the resistance of the voltmeter would be equal to the other resistance multiplied by the second reading and divided by the difference of the readings.

The resistance of most voltmeters is marked on the box or case, but the above would be available in case it was unknown.

With a Weston 150-volt range voltmeter satisfactory resistances can be measured from 100 to 2500 ohms, the most accurate being for resistances about equal to that of the voltmeter. With the low-reading voltmeter, from 0 to 5 volts, a range from 3 to 85,000 ohms may be measured.

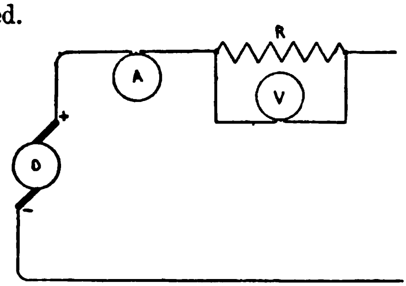


FIG. 187.—Connections for Measuring Resistance with Voltmeter and Ammeter.

To Measure Resistance with an Ammeter and a Voltmeter.—To do this it is only necessary to connect up the resistance in series with the ammeter and connect a voltmeter at the terminals of the resistance. Then, by Ohm's law, the resistance is at once calculated.

From above $R = \frac{V}{A}$ (Fig. 187).

Precautions when Measuring Resistance with Ammeter and Voltmeter.—See that the instruments are far enough apart so that neither will be effected by the other, and use no more current than is suitable for the resistance. See that all connections are good, and especially those of the voltmeter. It is better to connect the ammeter outside the voltmeter, for the error will be less if the ammeter measures the slight current through the voltmeter than if it were connected so that the voltmeter recorded in addition the fall of potential through the ammeter.

To Measure Resistance with a Voltmeter and Standard Resistance.—The circuit whose resistance is to be measured is connected in series with the standard resistance and a steady current sent through both. The voltmeter is connected around the standard resistance and then around the unknown resistance. The current being the same through both resistances, the differences of potential are directly proportional to the resistances. A typical connection is shown in Fig. 188 for measuring the resistance of an armature.

A few cells are connected up in series with the standard resistance and the armature whose resistance is to be determined. A voltmeter is connected to the terminals of the resistance and when

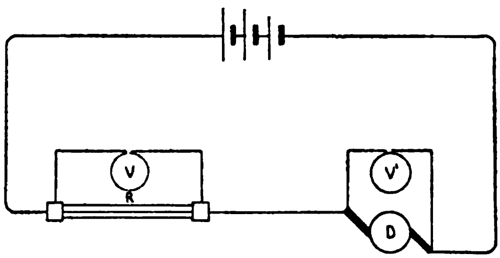


FIG. 188.—Connections for Measuring Resistance with Voltmeter and Standard Resistance.

current is established through the circuit, the fall of potential through the resistance is noted. When the same current is flowing, the voltmeter is connected to the brushes of the armature or to two opposite segments of the commutator, and the fall of potential noted. Calling R and D the resistances and V and V' the readings of the voltmeter, then the current C through R and D is, by Ohm's law,

$$C = \frac{V}{R} = \frac{V'}{D} \text{ or } D = \frac{V'R}{V},$$

whence D is readily calculated.

In this measurement, the standard resistance should be capable of carrying considerable current without heating, and the "ampere shunt" resistance can be used to advantage. The current should be steady, and the resistance of the voltmeter high, and the voltmeter itself low reading.

Standard Resistances.—If no resistances are available, they can readily be made on board ship. Knowing the resistance required, and its diameter and specific resistance, its length can be determined as given under the subject *Resistance.* Its calculated resistance should be checked by actual measurement by some of the methods given.

Calibration of Instruments.

Calibration is the process of determining the value of the current or voltage required to move the indicator to any or all parts of the scale. This may be done when making a new scale or in checking an instrument that has been in use. For example, suppose that an instrument has a resistance of 10,000 ohms, and that .001 ampere causes the pointer to move an inch from its zero point. By Ohm's law $E = C \times R$ or $E = .001 \times 10{,}000 = 10$ volts, so that point on the scale one inch from the starting point might be marked either 10 volts or .001 (one milliampere). When this instrument is connected between two points and current flows through it so that the pointer takes this position, it is then known that a current of .001 ampere is flowing through it, or that the difference of potential between the points is 10 volts. In a similar way the value of any other point on the scale may be determined.

All voltmeters and ammeters should be calibrated from time to time by comparison with some standard instruments. To be accurate they should be compared with absolute standards, but as they are not available on shipboard, it is usual to compare all instruments with some standard, which in turn might be calibrated on shore by reference to absolute standards.

Calibration of Ammeters.—To compare an ammeter with a standard they are connected in series and the same current is sent through both, the deflection of the needle of the standard being noted and that of the other being compared with it. If the instrument has not changed the readings should be the same.

The instruments should be placed far enough apart so that the magnetic field of one does not affect the other, and the instruments should be in the same relative position, that is, both level if the standard is correct in that position, or both vertical, as the case may be.

If a standard ammeter is not at hand, a standard resistance and a millivoltmeter may be used, and the current flowing through the resistance calculated, and this should be the value indicated on the ammeter under test. The connections are shown in Fig. 189.

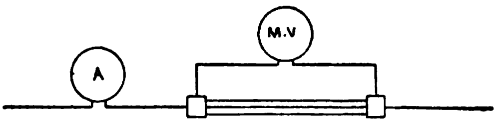


FIG. 189.—Connections for Calibrating Ammeters.

The instruments should be compared with increasing and then decreasing currents to check against errors of hysteresis and to see how far the instrument is affected by friction.

Calibration of Voltmeters.—Voltmeters are compared with a standard voltmeter by connecting all in multiple, so that all are subjected to the same voltage. The voltage is then changed to different values and the reading of the voltmeters is compared with the standard.

To Obtain Different Voltages.—In order that voltmeters can be compared throughout the range of the instrument, some means must be adopted of varying the voltages. A good method of doing this is to connect across the mains of a constant potential circuit, such as the lighting mains on ship, a piece of wire that will allow a small current to pass. A conductor of German silver wire is especially adapted for this, as its resistance per unit of length is uniform, so the fall of potential will be uniform.

By connecting the voltmeters in multiple along this wire any difference of potential may be obtained, and comparisons with the standard made. It is well to have one common terminal secured to one of the mains, and another common terminal may be moved along the wire. The connections are made in Fig. 190.

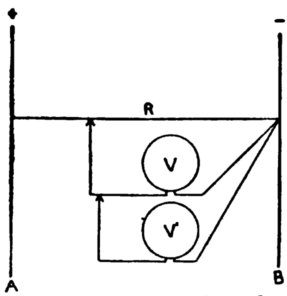


FIG. 190.—Connections for Calibrating Voltmeters.

A and *B* represent the mains and *R* the German silver resistance, *V* the standard voltmeter and *V′* the one under comparison.

To Connect Voltmeters to Increase their Range.—It may happen that a voltage is desired to be measured that is beyond the range of the voltmeter at hand. The range of the voltmeter may be doubled by placing it in series with an equal resistance. If the voltmeter reading to 150 volts has a resistance of 15,000 ohms, it will read to 300 volts when it is connected in series with an added resistance of 15,000 ohms or another voltmeter of the same resistance. This results from the fact that if the resistance of the circuit is doubled, twice as much pressure is required to send the same current through. If these two voltmeters are connected between two points whose difference of potential is 300 volts, each instrument will register 150 volts, the fall of potential through each being 150 volts. The total fall of potential will be the sum of the fall of potential through each instrument.

To Connect Voltmeters to Decrease their Range.—Most portable voltmeters are provided with two resistances, by means of which two scale readings are available, one for high and one for low differences of potential, and separate terminals are provided for putting these resistances in the circuit. It frequently happens that a high-range voltmeter is the only means at hand for measuring voltages, and a small difference of potential may be wished to be measured. Weston voltmeters are marked in single volts, but frequently they are not accurate within the first few divisions on the scale of the high-reading instruments. In this case it is better to connect the points between which the E. M. F. is required in series with the voltmeter and connect them both across high potential mains.

Suppose it was required to measure the E. M. F. of a battery with a voltmeter whose range was 150 volts. Connect the battery in series with the voltmeter and connect them both across the lighting mains, say an 80-volt circuit. If the voltmeter showed 78.5 or 81.5 volts, it would indicate that the battery had added or subtracted 1.5 volts, depending on how its poles were connected, and therefore the E. M. F. of the battery must be 1.5 volts.

Uses of the Testing Set.

The uses of the Queen-Acme testing set are taken from the circular issued by the makers of this instrument, Queen & Co., and which is furnished with the instrument.

To Measure Resistance.—Resistances are measured with the Queen-Acme as follows:

Connect the terminals of the resistance to be measured to the line posts *C* and *D*, and place the battery connectors on the two upper tips. This throws one cell of the battery into circuit, which is sufficient until balance is roughly attained. Now unplug the 100-ohm coil in each bridge arm, and place the commutator plugs for either high or low resistances. Remove plugs from the rheostat until the aggregate resistance unplugged is, as nearly as may be guessed, equal in value to that of the unknown resistance. Then press the battery key, and, holding that down, momentarily press the galvanometer key. If the galvanometer needle swings toward +, the resistance unplugged in the rheostat is too high and should be reduced. If the deflection is toward —, the resistance is too low and should be increased. By altering the resistance in this way a value will soon be found wherein a slight change either way will reverse the deflection of the galvanometer needle. The rest of the battery may now be put in circuit by placing the right-hand battery connector on the lower left-hand tip. If the keys be again pressed, first the battery key, then the galvanometer key, a greater deflection will be obtained than before for the same variation in the rheostat, and therefore the adjustment can be made more accurately. With bridge arms of equal value this is the best result that can be obtained, but by selecting more suitable values for the two arms a considerably higher degree of accuracy may be secured. A reference to the following table will show the best values of the bridge arms to determine any desired resistance.

The following table shows the values of *A* and *B* respectively, to be chosen when measuring any resistance within the range of the set:

Below	**1.5**		**ohms, make**	**A = 1, B = 1000**	**Plug for Low.**
Between	**1.5 and 11**		**" "**	**A = 1, B = 100**	
"	**11 " 78**		**" "**	**A = 10, B = 100**	
"	**78 " 1100**		**" "**	**A = 100, B = 1000**	
"	**1100 " 6100**		**" "**	**A = 100, B = 100**	**Plug for Low or High.**
"	**6100 " 110,000**		**" "**	**B = 1000, A = 100**	**Plug for High.**
"	**110,000 " 1,110,000**		**" "**	**B = 1000, A = 10**	
"	**1,110,000 " 11,110,000**		**" "**	**B = 1000, A = 1**	

Placing the Plugs.—In placing the plugs in the commutator it is sufficient to remember this:

First. Excepting when the two arms are of equal value, *always* make arm *A* the *smaller*.

Second. If the resistance being measured is higher than 6100 ohms, place the commutator plugs for high; if lower than 1100 ohms, for low. In the first case, the unknown resistance is found by dividing the larger bridge arm by the smaller, and *multiplying* the total unplugged resistance in the rheostat by the quotient. In the second case, the rheostat resistance is *divided* by the quotient. The arrows on the top of the set facilitate setting the commutator plugs. If measuring high resistance, set the plugs in the direction indicated by arrow *H;* if measuring low resistance, follow direction indicated by arrow *L.*

Example.—An example will illustrate the method of using the bridge. It is desired to measure a resistance say of about 1000 ohms. Connect the resistance to posts *C* and *D,* arrange the commutator in the direction of arrow *L,* place battery connectors on upper tips, and remove the 100-ohm coil from each bridge arm. From the rheostat unplug 1000 ohms, and upon pressing the keys the galvanometer needle swings to —. Unplug 100-ohm coil, and galvanometer needle swings to +. Try 1050 ohms, moves to —. Try 1070, still —. Try 1090, moves to +. With 1080, needle reverses again, swinging to —. Try 1085, swings to —. Try 1087, it swings to +. Try 1086, swings to —. The true value is, therefore, between 1086 and 1087. To secure more accurate results, change bridge arm *B* to 1000, and remove 10,860 ohms from rheostat. This proves too little. Try 10,865, and it is found too large. It is probable that with 10,000 ohms out no change in deflection will be noted smaller than will be produced by a change of 5 ohms in rheostat. We see that 10,860 is small and 10,865 large, the true value, therefore lies between them, or say 10,863.

Very Low Resistances.—In measuring very low resistances, excellent results may be secured by interpolation. Supposing a resistance of about .01 ohm is to be measured. Make the bridge arms 1000 and 1 respectively, and arrange the commutator with the plugs in the direction of arrow *L.* Unplug 10 ohms from rheostat, and

needle swings to +. Try 5 ohms, and it reverses, swinging to —. Another trial demonstrates that the correct value lies between 7 and 8. That is .007 and .008 ohm. Now to determine the result accurately note the values of the two reverse deflections when 7 and 8 ohms, respectively, are out. In the former case the deflection is — 1.4 divisions; in the latter case, + 4.1 divisions. The 8 comes more nearly balancing; or, in other words, the true value is more nearly 8 than 7. Now divide the larger deflection by the sum of the two deflections, and annex the quotient to the smaller value removed from the rheostat. $\frac{14}{25} = .56$ or .00756 ohm for the resistance desired.

To Compare E. M. F's. of Cells.—Connect in all of the cells in the set in the usual way, taking care, however, not to reverse them by crossing the battery cords. Plug the commutator only between *B* and *R*, and remove 1000 ohms from bridge arm *B*. Arm *A* should be all plugged *in*. From the rheostat unplug say 5000 ohms. Now, connect one of the cells, whose electromotive forces are to be compared with its positive terminal, to the + battery post, and its negative terminal to the line post *C*. Upon pressing the keys the needle swings one or the other way. If towards + unplug less resistance in rheostat, and if toward — add resistance to rheostat. A value will quickly be found wherein a variation of an ohm either way reverses the deflection. Now, take this value and add to it the resistance unplugged in arm *B*. This divided by the resistance in arm *B* gives the ratio between the potentials of set battery and test cell respectively. It will be noted that the division is decimal and consists merely in pointing off as many places as there are ciphers in the resistance unplugged from arm *B*.

This operation repeated with any number of cells gives their values in terms of the battery E. M. F. in the set from which their relative values may be obtained. Or, if desired, a standard cell may be used to replace the battery in the set, in which case the first measurement gives at once the value of the E. M. F. of the test cell.

If the E. M. F. of the cell or battery being tested exceeds that of the battery in the set, it is only necessary to reverse the positions of the two batteries, when the results are secured as before.

To Check a Voltmeter.—A voltmeter may be checked up, to determine its accuracy, while in service. Disconnect the battery of the set. Connect the circuit to the battery posts of the Queen-Acme set, positive lead to + post, negative lead to — post. Before doing this, remove say 10,000 from rheostat, plug commutator only between *B* and *R*, and remove 100 ohms from arm *B*. Now, connect a standard cell or one whose E. M. F. is known with positive terminal to + battery post, and negative terminal to line post *C*. Upon pressing both keys a deflection occurs towards + if rheostat resistance is too high; towards — if too low. A few changes will produce a result wherein a slight variation in the rheostat resistance reverses the galvanometer deflection. To find the E. M. F. on the line, add 100 to the rheostat resistance and point off two. Multiply this by the E. M. F., and the result is the desired E. M. F. If the standard is exactly one volt, the total resistance out represents the E. M. F. on the circuit.

The attainable accuracy is greater than could be secured with the best voltmeter, in fact, it is an excellent method of checking the accuracy of all voltmeters.

Battery Resistance.—To measure internal resistance of a cell, first compare its open circuit potential with the potential of battery in set as previously explained. Now, shunt it with a known resistance, say 100 ohms, and again measure its terminal potential. The difference between these values, divided by the shunt resistance, gives the current flowing. To find the internal resistance, multiply the resistance of shunt by ratio between first value measured and second. This method has one important feature; it determines the internal resistance under normal conditions of use, since the shunt may be given any desired value. One is enabled to give a low value to the shunt, and make repeated balances while the cell is discharging, thereby determining the effect of polarization.

As an example of the application of the Queen-Acme to the internal resistance of a battery, take say a silver chloride testing cell and determine its resistance. Measuring its potential in terms of test battery, we find it is .212 of the latter. Shunting it with 1000 ohms, and repeating the measurement we find .179 for the terminal E. M. F. The total resistance, therefore, is to the 1000

ohms shunt as 212 is to 179 or the total resistance $= \frac{212}{179} \times 1000 = 1184$. Deducing the shunt we have 184 ohms as the internal resistance of the cell.

To Check an Ammeter.—To check an ammeter with the Queen-Acme, secure a low resistance and proceed as follows: Connect the low resistance in series with the meter and run leads from it to the Queen-Acme set; one lead from the positive side of the + battery post, the outer from the negative side to the line post *C*. Join a standard cell between the battery posts; positive to + post, negative to — post. Plug commutator between *B* and *R*; remove say 10,000 from rheostat, and 100 from arm *B*. Balance in the usual way by changing rheostat resistance. Now, the difference of potential at the terminals of the shunt has been balanced against the standard cell, and is found by the directions previously given for comparing E. M. F's. to equal shunt

$$PD = \frac{1.44 \times 100}{R + 100} = \frac{144}{R + 100}.$$

To determine the current flowing, divide this result by the shunt resistance. As the shunt resistance has usually a decimal value, it is necessary merely to point off in the last operation.

Use of the Keys.—The primary use of the keys is very evident, that in the battery circuit to prevent current from flowing all the time, thus running down the battery, and that in the galvanometer to protect that when not in use. It has been stated in making a measurement, the battery key should be first pressed, and at an interval, the galvanometer key. The nature of certain resistances may cause the potential of any two points to be widely different when the current is starting or stopping and yet they may be at the same potential when the current is steady. A current can never rise or fall to its full value instantaneously, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady by first closing the battery key, and then closing the galvanometer key.

In measuring a resistance like that of an electromagnet in which there is great self-induction, or a long line in which there is electrostatic capacity, the proper use of the keys becomes very

important. Although there may be an exact balance, yet if the galvanometer key is closed first, the needle may be violently thrown, owing to the momentarily induced current.

In measuring the resistance of an electromagnet, the galvanometer must be placed some distance from it, so it will not be influenced by the magnetic field set up around it. The effect can be tested by opening and closing the battery switch, leaving the galvanometer key opened. If there is any movement at all of the needle, it is proof that some part of the circuit is disturbing it, and this should be corrected before the measurement proceeds any farther.

Earth Test.—If it is not possible to bring both ends of the unknown resistance to the bridge, the test can still be made by connecting one end to the bridge and connecting the far end to a good "earth" connection, and also making connection to earth of one pole of the battery. The earth being at the same potential, will act as though the two were connected to a common terminal. The terminal of the bridge where the far end of the resistance and the pole of the battery would connect is also connected to earth. The measurement is now made as before.

Uses of the Magneto.

This instrument finds constant use on board ship for locating breaks or faults in circuits, for locating grounds and to a limited extent for measuring certain high resistances. It is of particular use while wiring circuits and for tracing out breaks in bell circuits, and finds use, too, to a certain extent in testing out the various windings of a generator or motor, as it quickly locates faults or grounds.

To Test for Open Circuit.—On the outside terminals, there are usually connected two short pieces of connecting wires. To test a circuit, these leading wires are secured to the ends of the circuit, and the armature is rapidly revolved. If the circuit is closed, current flows through the armature, around the electromagnet and through the outside circuit, thereby causing the bell to ring. If the circuit is broken no current flows and the bell does not ring.

It is always well to short circuit the terminals and then revolve the armature to see if all the connections in the magneto itself are intact and the circuit continuous.

To Detect a Ground.—Connect one terminal to the circuit to be tested, and the other to a good "ground" or "earth" connection through a steam pipe, or to a bulkhead or the ship's side, seeing that the paint is scraped off to get connection with the bare iron. If there is a ground on the line, current will flow through the ground back through the ground connection and the bell will ring. If there is no bad ground, the bell will not ring.

To Locate a Fault in an Open Circuit.—Suppose a break showed on one leg of an electric-light circuit. Unscrew all the lamps on that circuit and ground both ends of the conductor. Go to a point about midway of the line, and at some junction box connect one terminal of the magneto to one end of the conductor where disconnected and the other terminal to ground. Ring through. If the bell rings, that part of the circuit is complete. Connect the other end of the conductor where disconnected to the magneto and ring through. If there is no ring, the break is in that part. Connect the circuit again and go to some other point in the direction of the break and ring through again both ways. A few trials like this will soon develop and discover the break.

To Test for Breaks, Leaks or Grounds in Generator Windings.—Treat them exactly as though they were separate circuits, first seeing that all circuits are disconnected from one another and the brushes raised from the commutator. To see if there is a leak from the series winding to the shunt winding, connect one terminal of the magneto to the series winding, the other to the shunt, and ring through. To test an armature for grounds, connect one terminal to the armature through a brush and the other to ground and ring through. The connections to be made will readily suggest themselves to obtain the desired result.

To Measure Resistance by a Magneto.—Each magneto has stamped on it the number of ohms through which current can be sent and consequently the bell rung. The ordinary resistance through which the bell can be rung varies from 15,000 to 30,000 ohms. Knowing the value for a particular magneto, the loudness

of the ringing furnishes a rough idea of the resistance being rung through. When the bell rings almost as strongly as when short-circuited, it shows the resistance is very low. When it does not ring at all, it shows that the resistance is above the value for that particular magneto. If it rings feebly, it shows the resistance is very high.

To Increase the Sensitiveness of a Magneto.—Although the resistance of a circuit may be so high that the bell will not ring through it, in some cases the continuity of the circuit may be shown by putting the hands in circuit. This is done by putting one terminal of the magneto between two fingers and touching the back of the hand to the end of the circuit. Wetting the fingers and back of the hand will add to the sensation of current.

Wrong Indications of a Magneto.—As a magneto gets old, the permanent magnets are apt to lose some of their magnetism, so the voltage for the same number of revolutions grows less, and the magneto will not ring through as high a resistance as when new. The magneto may be short-circuited and the bell rung through any resistance; or some of the connections may get broken or worn out, and the bell not rung through any resistance.

A magneto may sometimes ring by simply connecting it up to a circuit in which there is great capacity, even though the circuit is open, thereby giving a wrong indication. There is more or less capacity in all parallel circuits, and a magneto will sometimes ring when connected to the ends of a long coil of double conductor, such as lamp cord, even though the resistance to continuity of circuit may be millions of ohms.

Measurements of Insulation Resistance.

Insulation resistance may be tested either for the ohmic resistance of the insulation or for the ability of the insulation to withstand the potential to which it is ordinarily subjected.

If only the ohmic resistance is required the insulation may well be tested by the Testing Set, but for the ability to stand high potential as well as ohmic resistance the ohmmeter with a small magneto is preferable.

Insulation by Direct Deflection.—Insulation resistance may be measured by the testing set by direct deflection. Connect a known high resistance, say 100,000 ohms, one terminal to the line post *C*, one terminal to the + battery post. Remove all plugs from the commutator, and have all plugs in the rheostat, as any resistance unplugged in rheostat is in circuit with galvanometer and battery. Arrange battery tips so as to connect in one cell only. Now upon pressing the keys a deflection of about 8 divisions will be obtained. This deflection is due to the current from one cell through 100,000 ohms. If we multiply the resistance by deflection we have that resistance through which one cell will produce a deflection of one scale division. This is the constant of the galvanometer.

Now, replace the known high resistance by one whose value it is desired to know, and add enough cells to produce as large a deflection as possible. Multiply the constant of the galvanometer, usually expressed in megohms, by the number of cells and divide by the number of scale divisions deflection. The result is the desired resistance expressed in megohms.

If a high resistance is not at hand, one may be readily made for temporary use by marking with a soft pencil on a strip of ground glass. Connect the glass by means of tinfoil ends to the posts of the set, and measure its resistance, adding or removing a small amount of graphite until the desired value is secured.

Method by Testing Set.—The following is the method generally used as a quarterly test required by the regulations. One leading wire is taken from one terminal of the unknown resistance of the bridge to one bus bar on the switchboard. The connections of all voltmeters, ammeters and ground detectors are broken, as well as connections from the generators, this last effected by leaving the main headboard switches open. Another leading wire leads from the other terminal of the unknown resistance to a good earth connection. All lamps in all the different parts of the ship are unscrewed from their sockets, and it is well to test each circuit for continuity by the magneto, as this will tell whether any lamps have inadvertently been left in place. Open all the switches controlling the different circuits at the switchboard. When all ready to go on with the measurement, close a switch connecting one leg of the

circuit to be tested to the bridge. As all connections are broken, the circuit can only be completed through grounds or leaks along the one leg of the circuit back to the earth connection to the bridge. Measure the resistance by the bridge or at least ascertain that it is over some fixed value, say 2 megohms, which it should be in a good circuit. Record the result. Open the switch and close another on the same bus bar, repeat the measurement and record it, and so on until measurements on all circuits have been made on the same bar, say all the + legs. In the case of searchlight circuits, see that the carbons are run apart, and in motor circuits that the circuits are disconnected at the brushes.

After finishing all the + legs, disconnect the leading wire from the + bus bar and connect it to the — bar, and repeat all the above measurements, recording the results in tabular form, numbering the circuits and distinguishing the legs of a circuit by + and —.

The result of the above measurements will give the insulation resistance of each leg of each circuit to earth, and to obtain the total resistance of each circuit to earth add the reciprocals of the resistances of each leg, and take this receptacle.

After the above series of measurements has been made, disconnect the leading wire from the earth connection and take it to the terminal of the bus bar not already connected. Now close both switches of a circuit, leaving all the others open, and all lamps being disconnected, current is only established through leaks from one leg of a circuit to the other. This is a necessary measurement as it might happen that the resistance of each leg to earth was very high, but that from one leg to the other was very low. Repeat this measurement for each circuit on the switchboard.

After this series of measurements is completed, then close all the switches and the resistance will be that of all circuits connected in parallel, which in the poorest installation should not fall under one-half megohm.

Machine Insulation Resistance.—The testing set can be used in a similar manner to test the ohmic insulation resistance of the different circuits of generators and motors. The different windings are disconnected, the brushes raised and connections to the switchboard broken. Keeping one terminal of the unknown resistance to

earth, the other may be connected to the different parts and windings, and measurements taken and recorded, as from armature to earth, series winding to earth, shunt winding to earth, etc. By making the proper connections by the leading wires from the bridge such insulation resistances can be made, as armature to series winding, or to shunt winding, or to engine shaft, or to frame, or to earth; or from shunt to series, shunt to armature, shunt to shaft, or such other combinations as will suggest themselves for examining the goodness of insulation.

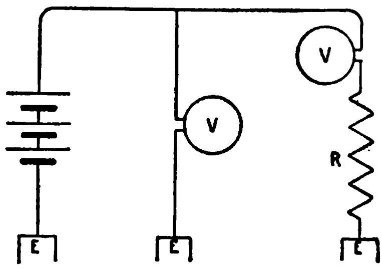


FIG. 191.—Battery Connections for Measuring Insulation Resistance.

Method by Drop of Potential Using Battery and Voltmeter.— The method of using the battery and voltmeter is shown in Fig. 191.

Let $E =$ E. M. F. of battery,
$b =$ resistance of battery,
$X =$ resistance of voltmeter,
$d_1 =$ deflection of voltmeter connected across battery terminals,
$d_2 =$ deflection of voltmeter in series with insulation resistance,
$R =$ insulation resistance,
$C =$ current through battery, voltmeter and R,

then

$$C = \frac{E}{R + X + b} \text{ and } C = \frac{d_1 - d_2}{R},$$

or

$$\frac{E}{R + X + b} = \frac{d_1 - d_2}{R} \text{ and } E = d_1,$$

whence

$$R = \frac{(X + b)(d_1 - d_2)}{d_2};$$

b is so small that it may be neglected.

Method by Voltmeter.—The method described of measuring insulation resistance by means of the bridge necessitates stopping the generators, or at least cutting off the current from the switchboard, but the voltmeter uses the generator current as the source of supply. The only instrument required in making this measurement is a portable voltmeter of known resistance, and the necessary connections can be made in a few minutes time, if they are not part of the switchboard installation.

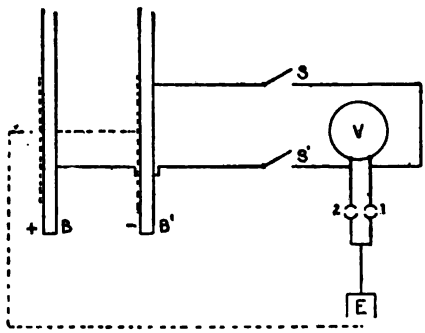


FIG. 192.—Connections for Measuring Insulation Resistance by Voltmeter.

In Fig. 192 B and B' are the bus bars connected to the generator terminals. V is the voltmeter, each terminal having a connection to earth through the plug switches 1 and 2. The bus bars are connected to their respective terminals of the voltmeter through the switches s and s'.

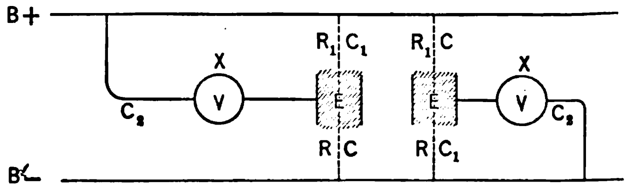


FIG. 193.—Voltmeter Connections to Ground.

The values of the insulation resistance of B and B' to earth may be deduced by a consideration of the connections shown in Fig. 193.

When the voltmeter is connected between B, the $+$ side, and earth E, there may be leaks from B to E and from B' to E.

Let V = difference of potential between B and B',
V' = deflection shown when B is connected to earth,
V'_1 = deflection shown when B' is connected to earth,
X = resistance of voltmeter,

then

$$C_1R_1 + CR = V \text{ and } C_2X + CR = V,$$
$$C_1R_1 = C_2X = V - CR = V', \quad C_1 + C_2 = C.$$

The joint resistance of R_1 and X is

$$\frac{R_1X}{R_1+X},$$

and

$$C\left(\frac{R_1X}{R_1+X}\right) = V' \quad C = \frac{V-V'}{R},$$

or

$$\frac{V-V'}{R}\left(\frac{R_1X}{R_1+X}\right) = V' \text{ and } R = \frac{V-V'}{V'}\left(\frac{R_1X}{R_1+X}\right). \tag{1}$$

This shows that the value of R, the insulation resistance of B' to earth, depends on the value of the insulation resistance of B to earth. If the voltmeter is connected between B' and earth and gives a deflection V'_1, a similar deduction will give R_1 in terms of R, thus

$$R_1 = \frac{V-V_1'}{V_1}\left(\frac{RX}{R+X}\right). \tag{2}$$

From equations from (1) and (2), the values of R and R_1 will be found to be

$$R = \frac{X(V-V'-V_1')}{V'}, \tag{3}$$

and

$$R_1 = \frac{X(V-V'-V_1')}{V_1'}. \tag{4}$$

If the $+$ leg is not grounded, $V'_1 = 0$, and

$$R = \frac{X(V-V')}{V'}, \tag{5}$$

and if the — leg is not grounded, $V_1 = 0$, and

$$R_1 = \frac{X(V-V_1')}{V_1'}. \tag{6}$$

Example.

A direct reading voltmeter, having 16,000 ohms resistance is connected from the + main to earth. The voltmeter shows 2.6 volts and the difference of potential between mains is 110 volts. Find the insulation resistance between the — main and earth, assuming that the insulation resistance of the + main to earth is (1) infinite; (2) the same as the — main to earth, and (3) one-tenth of the — main to earth.

If the insulation resistance of the + main is infinite, that leg is not grounded, and from equation (5)

$$R=\frac{X(V-V')}{V'}=16{,}000\times\frac{110-2.6}{2.6}=660{,}900 \text{ ohms.}$$

Under condition (2) $V'=V'_1$ and from equation (3)

$$R=\frac{X(V-V'-V'_1)}{V'}=16{,}000\times\frac{110-5.2}{2.6}=644{,}900 \text{ ohms.}$$

Under condition (3) $V'_1=10\ V'$,

$$\text{and } R=\frac{X(V-V'-V'_1)}{V'}=16{,}000\times\frac{110-28.6}{2.6}=500{,}900 \text{ ohms.}$$

Suppose it is required to measure the insulation resistance of the — legs to earth. One circuit is taken at a time, the others being cut out; both section switches on the bus bars are closed. The switch s' is closed and plug switch is inserted in 1. The only current then through the voltmeter is from the + bus bar through the voltmeter, through the switch 1 to earth and from earth to earth leaks along the — leg, and thence to the — bus bar. All the — legs can be tested in this way in a few minutes, recording for each circuit the reading of the voltmeter.

To test the + legs, take one circuit, keep both section switches closed; close s, open s' and insert plug in 2. The current is then from + bus bar to leaks along the + leg to earth to the voltmeter through 2, through the voltmeter and switch s to the — bus bar. Record the reading of the voltmeter and do the same for each leg.

The bus bar voltage can be determined by opening both 1 and 2 and closing s and s'. Having this voltage and the drop due to earth leaks, we have the data necessary for calculating the insulation resistances.

Knowing X and V and assuming a value for R beyond which its actual value is not desired, V' can be calculated. If a reading shows above this calculated value, R is less than the assumed value, and vice versa.

Suppose it was not wished to know the actual resistance, provided the resistance to be measured was over 2 megohms, and the voltmeter had a resistance of 13,000 ohms, and we were using an 80-volt circuit then

$$2{,}000{,}000 = \frac{13{,}000 \times 80}{V'} - 13{,}000,$$

or

$$V' = \frac{1{,}040{,}000}{2{,}013{,}000} = \tfrac{1}{2} \text{ volt practically.}$$

If the voltmeter showed $\frac{1}{2}$ volt or less, the insulation resistance for the particular part measured would be 2 megohms or over.

This is a very rapid and easy method and the insulation of the different legs of the different circuits to ground can be tested at any time while the generator is running, and besides it has the advantage of the high potential of the running machine. The only observations are V and V' for each measurement and these can be recorded for each circuit, and the calculations can be made after the tests are finished, the whole operation only consuming a few minutes.

Method by Ohmmeter.—To measure insulation resistance by this method requires the use of an ohmmeter and a magneto. The leading wires from the magneto are connected to the proper terminals on the ohmmeter and the circuit to be tested is connected to the other set of terminals. The same preliminary operations as in the other methods are necessary. If one leg is to be tested to earth, one terminal is connected to the leg and the other terminal to earth. The armature of the magneto is rapidly revolved and current is sent through the ohmmeter and circuit, being completed through grounds or leaks. The ohmmeter measures directly the resistance of the circuit being tested, and the result is read off directly from the scale. This is by far the most rapid and convenient method of making this test, and not only is the ohmic resistance of the insulation measured, but the circuit is tested for its ability to stand the high potential developed by the magneto.

It sometimes happens that the resistance measured with a low potential differs from the same resistance measured with a high potential, due to the electrostatic attraction of the conductors under the influence of high potential.

The magneto and ohmmeter can be used to test out the different windings and insulation resistance of the various parts of generators and motors in a way similar to that described for the magneto alone, and under the heading "Machine Insulation Resistance."

Measurement of the Resistance of Generator Windings.

As an illustration of the general methods of measuring resistances by the use of instruments furnished to ships, a general description will be given of the measurement of the resistances of the different parts of a compound generator; namely, the shunt winding, the series winding and the armature. These values are usually furnished as part of the data when the generators are installed, but it may become necessary to verify them, or to make the measurements in testing for faults or breaks.

The Shunt Winding—By the Bridge.—The resistance of the shunt field is usually sufficiently large to be measured by means of the bridge, the ends of the winding being disconnected from the generator terminals and connected to the terminals of the bridge for the unknown resistance. It requires some skill in making this measurement, as when current is sent around the shunt coils or the circuit is broken at the key, the momentary self-induction reacts on the needle of the galvanometer and gives it a motion which is not its true motion due to the current flowing around it. This can be obviated to some extent by keeping the battery key pressed down some time before the galvanometer key is pressed, and releasing the latter key before the battery key. In making this measurement by the bridge, if possible the balance arms should be equal, so that the resulting reading in the rheostat arm may not have any error multiplied or divided.

By Voltmeter and Ammeter.—A more satisfactory way of measuring this resistance is by means of a voltmeter and ammeter, connecting the former to the shunt field terminals and disconnecting one end of the field windings and inserting an ammeter in series with it.

Then start the generator and let it build up to its full voltage, and the instant it has attained this voltage, read both the voltmeter and ammeter. Dividing then the number of volts by the

number of amperes will give at once the resistance of the shunt winding in ohms. It is necessary to take the readings the moment full voltage is reached, because the moment current flows around the shunt coils, heat is generated in them, thereby increasing the resistance. The first readings will give the cold resistance, or the resistance of the copper itself. It is usually necessary to know the hot resistance of the shunt winding, which is calculated by taking the readings of the voltmeter and ammeter after running for two or three hours. If the field has four shunt spools, the total resistance divided by four should give the resistance of each spool, though it is always better to check the measurement by shifting the voltmeter to the terminals of each field spool separately, leaving the ammeter in circuit as before.

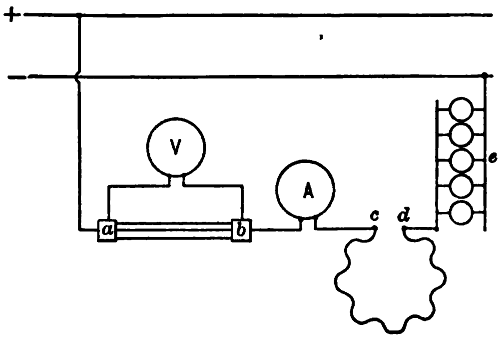


FIG. 194.—Connections for Measuring Resistance of Series Winding.

Series-Winding Resistance.—The resistances of the series windings and armatures of generators and motors are so small, usually less than .01 of an ohm, that measurement by the bridge is not satisfactory. The method generally practiced and which gives good results, is the fall of potential method. This method of measuring the resistance of an armature has been given under the heading, "To Measure a Resistance with Voltmeter and Standard Resistance," but the following method is a little more practical and with more details:

The connections for making measurement of the series winding of a generator are shown in Fig. 194. For this measurement, cur-

rent is taken from the switchboard, or some convenient mains or feeder, being energized by another running machine. The standard resistance a, b, is connected in series with the series winding, and in addition, a resistance e is inserted in series, to steady the current and to prevent short-circuiting the running machine. The standard resistance a, b, should have a resistance somewhat near the supposed resistance of the unknown resistance, say .01 ohm. The resistance e can readily be made of lamps, so arranged in series and parallel as to give almost any desired result and being heavy enough to withstand the heavy currents.

Only enough current is required from the running generator to give a good readable deflection on the voltmeter, and it is well to insert an ammeter in circuit, as shown at A, in order to know just what current is flowing. It is best to start with a low-testing current and gradually work up to the value decided on.

A low-reading portable voltmeter is used and is connected to the terminals a and b, and the current varied by changes in the lamp bank until a good deflection is obtained. The final reading of the voltmeter is recorded and the current being kept steady, the voltmeter is connected to the terminal of the series winding and the reading noted. With the three known quantities, the two readings of the voltmeter and the known resistance, the unknown resistance is calculated by the formula previously given,

$$R' = \frac{V'R}{V},$$

from which it is seen that the accuracy of the measurement depends on the accuracy of the known resistance.

For very low resistances a current of 10 to 100 amperes may be necessary and a voltmeter reading to thousandths of volts.

Armature Resistance.—The same method can be used to determine the resistance of an armature, by disconnecting two ends from the commutator and connecting them in series with the known resistance, or by connecting the brushes in circuit with the resistance. If the last method is used, the brushes must make good contact with the commutator, and all other connections broken, and the value obtained will depend on the number of brushes and on the manner in which they are connected.

Contact Resistances.—The fall of potential method, with a high resistance, low-reading voltmeter, may be used to determine the goodness of contacts in binding screws, or from terminal leads to the brushes, or from the brushes to the commutator. Good contacts should show very low resistances which would be indicated by low readings of the voltmeter.

Measurement of Inductance.

The practical unit of self-induction is the self-induction of a conductor which is cut by lines of force 10^8 times when the current

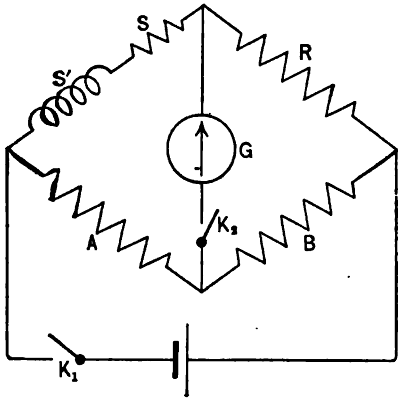


FIG. 195.—Connections (First Operation) for Measuring Inductance.

flowing in it undergoes a change of one ampere. If this cutting of lines of force takes place in one second, the self-induction developed is one volt. The E. M. F. of inductance is proportional both to the rate of change of current and to the inductance.

Accurate measurements of inductance require special laboratory apparatus, but a satisfactory method of determining the inductance of coils such as are used with wireless equipments is found by using the instruments and apparatus usually furnished with ship outfits. The method described requires an ordinary testing set and a condenser of known capacity. The latter should be found in the wireless equipment.

In Fig. 195 is shown the ordinary connections of a Wheatstone bridge, or those of the testing set.

A and B are the ratio arms, R the rheostat arm, while in the position of the X, or unknown resistance, is inserted the inductance coil to be measured, S^1, in series with a non-inductive resistance S.

The first step is to obtain a balance by the steady current from the battery. This is done by giving suitable values to the ratio arms A and B and then adjusting R until no deflection is observed in the galvanometer, when, first K_1 and then K_2 are closed. In the ordinary test, the value in the R arm would be that of the ohmic resistance of S^1 and S.

After a balance is obtained there is current flowing through all the resistances except the branch containing the galvanometer. If now this current is interrupted by opening K_1, the field surrounding S^1 will collapse and the lines of force will cut all the turns of the coil, giving rise to an E. M. F. of induction which will produce a current that will flow through all the branches, dividing among them in proportion to their resistances. The portion that flows through G will produce a deflection of the needle.

The E. M. F. of self-induction $= \frac{N}{t}$ where $N =$ total number of cutting lines of force and $t =$ time for the collapsing lines to disappear. By definition $N = LC$, where C is the current in S^1 and the E. M. F. of self-induction $= \frac{LC}{t}$.

The mean current of self-induction is equal to the E. M. F. of self-induction divided by the total resistance. The total resistance may be considered as made up of S^1, S and A in series connected with R, B and G in parallel. Calling Y the combined resistance of R, B and G, the total resistance is $S^1 + S + A + Y$, the mean current of self-induction $= \frac{LC}{t(S^1 + S + A + Y)}$ and the quantity Q_1 of electricity which flows through the circuit $= \frac{LC}{S^1 + S + A + Y}$.

A certain fraction of this quantity Q_1 flows through the galvanometer and produces deflection θ_1, the quantity depending on the resistances of the various parts.

The second part of the operation consists in replacing S^1 and S by a suitable condenser and resistance, as shown in Fig. 196. Here

K is a condenser shunted by a resistance Z, which is given such a value that without changing A, B or R a balance is again obtained when the keys are closed. In other words, Z is equal to the ohmic resistance of S^1 and S in the first measurement.

The quantity of electricity Q now on the condenser plates is equal to the potential to which it is charged times the capacity K of the condenser. This difference of potential is equal to the current flowing in that branch times the resistance, and since

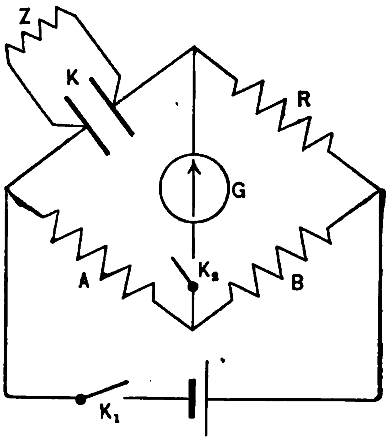


FIG. 196.—Connections (Second Operation) for Measuring Inductance.

$Z = S + S^1$, the potential difference is equal to CZ, and the quantity on the condenser plates is CKZ. When K_1 is now opened, K_2 being closed, this quantity CKZ discharges partly through Z and partly through A and Y. The proportion of Q which discharges through $A + Y$ is

$$Q_2 = Q \times \frac{Z}{Z + A + Y} = \frac{CKZ^2}{Z + A + Y}.$$

The proportion of Q_2 that discharges through the galvanometer is the same as the proportion of Q_1 which passed through it in the discharge of the induction coil S^1, and since these fractions are proportional to the two throws θ_1 and θ_2 of the galvanometer, the following relation holds:

$$\frac{\theta_1}{\theta_2} = \frac{Q_1}{Q_2} = \frac{LC}{S^1 + S + A + Y} \times \frac{Z + A + Y}{CKZ^2},$$

and since $S^1 + S = Z$

$$\frac{\theta_1}{\theta_2} = \frac{L}{KZ^2} \text{ or } L = KZ^2 \frac{\theta_1}{\theta_2}.$$

All the factors of this last expression are known or can be found and L can then be calculated. If Z is found in ohms and K is in farads, L will be given in henries.

In practice it is a very tedious operation to obtain an exact balance with the inductance in circuit, and under ordinary conditions, the throw of the needle may be due to want of exact balance rather than to the induced current in the coil S^1, which is that sought. The resistances A, B and R should be equal and approximately equal to that of the galvanometer and the final adjustment for balance should be made by S and a resistance in series with it which can be made the slide wire of a meter bridge, if at hand, or a piece of German silver wire, which can be slid along its contacts. The galvanometer should be short circuited while making the first adjustments, and if a large deflection is produced when the short circuit is removed, the adjustment of the slide wire should be continued until a deflection of one or two centimeters is produced.

The mean of several throws should be taken, remembering to close the battery circuit first and then the galvanometer circuit. The battery should be reversed and the operation repeated several times, taking the mean of all the throws. The arrangement of keys should be such that the short circuit on the galvanometer is opened just an instant before the battery circuit, so the impulse given to the galvanometer coil is due to the induced current in S^1 and not to want of perfect balance.

A special device has been made, called the **secohmmeter,** which is designed to rapidly reverse the battery current and to open the galvanometer short circuit an instant before the battery circuit.

Secohmmeter Method.—The method described in the preceding section has the disadvantages of all methods involving deflections of a galvanometer needle. With standards of induction and other laboratory apparatus, including a secohmmeter, the principle of the

Wheatstone bridge may be used as a *nil* or *zero* method. This is illustrated in Fig. 197.

$L_1 L_2$ are the two inductances to be compared, whose resistances are R_1 and R_2, connected up as a bridge with the non-inductive resistances R_3 and R_4. A balance for steady currents can be obtained if $R_1 : R_2 :: R_3 : R_4$. A balance for varying currents can be obtained if $L_1 : L_2 :: R_3 : R_4$. If a balance of the inductance does not exist, it can be detected with a direct current by making and breaking the battery circuit. The galvanometer needle will give a

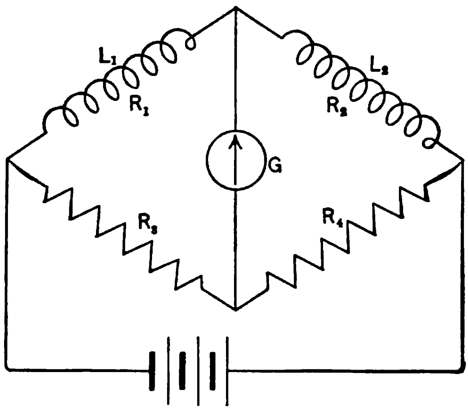


FIG. 197.—Connections for Measuring Inductance.

deflection one way when the circuit is broken and in the opposite direction when it is made. The deflection is due to momentary currents and the method is not sensitive. If, instead of making and breaking the battery circuit, the circuit is reversed, the effect on the needle will be doubled. If the circuit is rapidly reversed and between each reversal the galvanometer circuit is reversed, the effect on this circuit will always be in one direction, and will be greater as the speed of the reversals is increased.

The secohmmeter effects the reversal of the battery and galvanometer circuit. Fig. 198 shows the connections, using inductances whose values are known.

R_1, R_2 and R_3 are non-inductive resistances, L_1 and L_2 are known inductances, L_1 of fixed value and L_2 of variable value. L_3

is the inductance to be measured. R_4 is a stretched wire slightly greater in resistance than the smallest amount by which R_3 can be varied.

The figure shows in the battery commutator of the secohmmeter at the bottom that the battery circuit is just about to be reversed

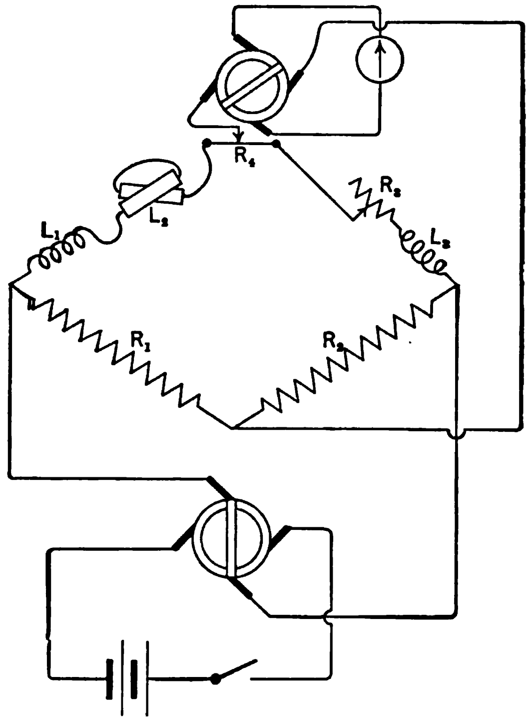


FIG. 198.—Connections for Measuring Inductances. Secohmmeter Method.

and will send a current through the galvanometer in one direction due to lack of balance of the inductances. It is assumed that the balance for resistance has been obtained. A turn of 90° of the commutator will again reverse the battery and send a current through the galvanometer, but in the meantime its commutator has turned through 90°, as both commutators are secured to the same shaft, and it is also reversed; consequently the galvanometer is sub-

jected to a pulsating current which is always in the same direction. L_2 is varied until no deflection is shown when the commutators are rapidly turned. With L_1 and L_2 known, the value of L_3 is readily obtained. L_1 could be dispensed with, if, on turning the standard variable inductance L_2 in its extreme positions, a deflection is shown first in one direction and then in the other, for under those conditions a position of balance could be found.

Whenever the values of the ratio arms R_1 and R_2 are changed and if L_1 is used, the balance for resistance with steady current must be obtained before the balance for inductance.

Measurement of Capacity.

The capacity of a condenser depends upon the two factors, potential and quantity. A large quantity of electricity applied to a condenser of small capacity will raise its potential to a high value, in the same way that a large quantity of water poured in a vessel of small diameter will raise the water level to a considerable degree. Expressed in symbols

$$Q = KV$$

where

$Q =$ quantity of electricity,
$K =$ capacity of condenser,
$V =$ potential to which condenser is raised.

In order that the expression $Q = KV$ may be true, it is necessary that all factors must be expressed in the same units; thus if K is expressed in farads, V in volts, Q will be expressed in coulombs.

The absolute measurement of capacity requires the use of laboratory apparatus, one method involving the use of a ballistic galvanometer. This is simply a galvanometer which is designed to reduce damping of the needle to a minimum so that it swings freely to a maximum throw under the impulse of a quantity of electricity discharged through its coils and comes to rest after a series of swings of constantly diminishing amplitude.

The quantity of electricity contained in a condenser may be measured by discharging it through a ballistic galvanometer, when the following expression holds:

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$$Q = \frac{K^1 \theta t}{\pi}$$

where

$K^1 =$ the constant of the galvanometer,

$\theta =$ the *angular* distance the needle moves expressed in radians,

$t =$ the time in secs. of one-half vibration.

The galvanometer constant is furnished with the instrument by the makers, θ is measured and t is calculated by taking the time it takes the needle to make a convenient number of half vibrations and taking the average.

To make a measurement, it is necessary to charge the condenser by connecting its terminals to a fairly constant current cell, when the condenser will become charged to the potential of the cell. The condenser is then discharged through the galvanometer, and the other factors are found.

Comparison of Capacities.

Bridge Method.—A convenient method of comparing one condenser of unknown value with one of a known value is by the *method of balances,* or *zero method,* the arrangement being somewhat similar to that of a Wheatstone bridge. The connections for making this test are shown in Fig. 199.

K_1 and K_2 are the two condensers to be compared, R_1 and R_2 variable resistances, the rheostat arms of two testing sets serving this purpose, G is a galvanometer of one of the testing sets, B a cell, K a double throw switch for either charging or discharging the condensers.

R_1 and R_2 are so adjusted that the galvanometer shows no deflection either when K is closed up or down, that is, either on discharge or charge. When this condition exists, the following relation holds:

$$\frac{K_1}{K_2} = \frac{R_2}{R_1}, \tag{1}$$

from which, knowing three of the quantities, the fourth may be found.

Equation (1) is true from a consideration of the following: When no current is flowing through G, the points c and d are at the same potential and therefore the difference of potential between b and c is the same as that between b and d. By Ohm's law this potential difference is equal to the current in each branch times the resistance of the branch, or the currents in R_1 and R_2 are inversely proportional to the resistances. The time during which the con-

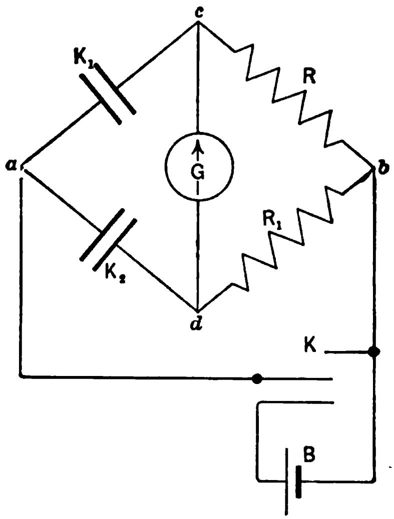

FIG. 199.—Bridge Connections for Comparing Capacities.

densers are discharging is the same for both, and as the quantities discharged are equal to the currents times the times, it follows that the quantities are inversely proportional to the resistances, or

$$\frac{Q_1}{Q_2} = \frac{R_2}{R_1}.$$

After a balance is obtained the points c and d are always at the same potential, and therefore the condensers must always be charged to the same potential and the quantity of electricity on each must be proportional to their capacities, or

$$\frac{K_1}{K_2} = \frac{R_2}{R_1}.$$

Induction Coil Method.—A very convenient method in the wireless room is to make use of an induction coil, or the transformer, and replacing the galvanometer by a telephone receiver. The connections are exactly similar to Fig. 199, replacing the galvanometer by the telephone, and inserting the secondary coil of the induction coil between a and b and connecting one or two cells in series with the primary coil. Some means must be provided for rapidly making and breaking the primary circuit.

The effect of the making and breaking of the current in the primary is to set up increasing and decreasing currents in the secondary. Each *make* charges the condensers and they discharge on *break* and are again charged in the opposite direction and then discharged. When the balance is perfect there is no potential difference between the points c and d and no sound will be heard in the telephone, but if the balance is not perfect a buzzing sound will be heard owing to the rapidly alternating currents through the receiver.

Wave Meter Method.—The expression for the number of oscillations in a closed circuit containing both inductance and capacity is given by the formula

$$n = \frac{1}{2\pi\sqrt{KL}},$$

and the wave length is equal to the velocity of propagation divided by the number of waves, and calling λ the wave length, we have

$$\lambda = V \times 2\pi\sqrt{KL}. \qquad (1)$$

The method consists in discharging the condenser through a spark gap in a circuit containing a known inductance and by means of a wave meter measuring the wave length. In equation (1) everything is known but K, which can be calculated, calling V the velocity of light 3×10^8 meters.

Uses of Potentiometer.

One of the primary uses of a potentiometer, that of comparison of E. M. F.'s of electric cells with that of a standard cell has been mentioned under the description of the instrument in the preceding chapter. Some of its other uses will be considered.

To Measure High Voltages.—It is evident that the instrument as previously described will not measure voltages higher than 1.6 volts and to measure higher values than this recourse is had to so-called "volt boxes." These consist of high resistances with one or more taps at a known part of it, as 1/10, 1/100, 1/1000, etc., as illustrated in Fig. 200.

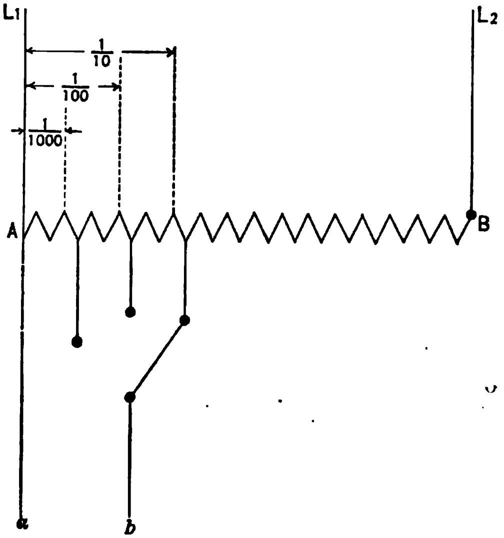

FIG. 200.—Connections of Volt Box for Potentiometer.

AB represents a high resistance with taps taken off from points representing 1/10, 1/100, 1/1000 of its value. These are connected to contacts over which a contact arm moves by which these tap-off points are connected to the potentiometer by means of the leads *a* and *b*. The leads between which the potential difference is sought are connected to the extremities of *A* and *B*.

The standard cell is connected in place, setting the contact points to the certified value of its E. M. F. With all the protecting resistance in series with the galvanometer, its circuit is made and the current is regulated by the resistance in series with the power cell until the galvanometer shows no deflection. The protecting resistance is gradually cut out and when all is out and the balance is

still maintained, the standard cell is cut out and the potentiometer points E. M. F. are connected to the leads *ab* of the volt box. In doing this it is necessary to see that the positive side of the line is connected to the same terminal that the positive terminal of the standard cell was connected. After the points *ab* are connected to the potentiometer a balance is again obtained by moving the contact points without disturbing the regulating resistance, and the voltage is read off from the position of the contact points. If the lead *b* is connected to the 1/10 tap-off point, the voltage read off is multiplied by 10 to obtain the difference of potential between the lines L_1 and L_2. The actual measurement gives the potential difference across 1/10 of the whole resistance of the volt box, and assuming the resistance to be uniform, the whole would be 10 times this value.

To Calibrate Voltmeters.—In the above connections for measuring high voltages, the true potential difference between L_1 and L_2 is obtained. If a voltmeter is connected across them, a certain value will be indicated, and if it is not the same as the value found by potentiometer measurement, it must be in error by the amount of the difference.

To calibrate a voltmeter over a considerable portion of its scale requires a means of producing potential differences which correspond to the markings along its whole scale at more or less regular intervals. Thus to calibrate a 150-volt instrument on a 220-volt circuit, a resistance should be used across the line that would give a suitable small current, say 5 amperes. The leads to the volt box and voltmeter should be connected in parallel with one lead connected to one end of the resistance and the other connected at regular intervals along the resistance to give as many points as desired. The potentiometer and volt box would then measure the potential drop from one line to the point on the resistance to which the other instrument lead was connected, and the voltmeter leads being in parallel, the voltmeter would give its reading at the same time.

To Measure Current.—Current can readily be measured by means of the potentiometer and standard low resistances, such as .1, .01 or .001 ohm. As the resistances are so small, the fall of potential across them is also small, and this difference of potential can readily

be measured by connecting the terminals of the resistance to the potentiometer and connecting the resistance in series with the current circuit. Knowing the difference of potential and the resistance the current is at once known.

To Calibrate Ammeters.—To do this, it is only necessary to make the connections above described and connect the ammeter in the current line with a suitable resistance for varying the current. The potentiometer and ammeter readings are taken at the same time, the true current calculated and compared with that shown by the ammeter.

To Measure Resistances.—With the aid of the apparatus used to measure current, the resistance of conductors may easily be measured. One of the standard resistances is connected in series with the resistance to be measured and both are included in a circuit containing one or more secondary cells to give a steady current. The difference of potential across the standard resistance is then measured by the potentiometer and also that across the resistance to be measured. As the current through each resistance is the same, the resistances are proportional to the differences of potential.

If the resistance to be measured is large, it may be that the drop of potential across it will have to be measured by the aid of the volt box and both resistances connected to high voltage lines in order to get a suitable current. If the current value times the value of the standard resistance is greater than the direct reading capacity of the potentiometer, the volt box will also have to be used to measure the drop across this resistance.

CHAPTER XXII.

FAULTS OF GENERATORS AND MOTORS.

A generator or motor considered simply as a mechanical machine is a very simple affair and the parts in which troubles may arise are few in number, the only moving or wearing parts being the commutator, brushes and bearings. To make it a complete electrical machine, to these may be added the armature core with its windings and the field pieces with the field windings.

Troubles may occur in any of these parts due either to faults within the machine itself, or to faults occurring outside the machine, in the external load that the generator or motor is supplying, the effects being conveyed to the machine and manifested there.

Every fault has its effect and the same effect may be traced to widely different faults, and a fault may produce one or more different effects. In order to definitely determine the proper relation between faults and effects, we may either tabulate the faults and trace the effects, or tabulate the effects and assign to them the faults.

The following table is self-explanatory and shows how intimately the different faults are connected, and with its help the cause of any particular fault may be traced.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
1. Too high voltage.	1. Too high speed of engine.	1. Voltmeter reads greater than standard, and lamps burn with undue brilliancy.	1. Slow the engine.
	2. Too strong magnetic field.	2. Same.	2. Introduce more resistance in shunt field.
2. Too low voltage.	1. Too low speed of engine.	1. Voltmeter shows lower than standard and lamps burn dimly.	1. Increase speed of engine.
	2. Too weak magnetic field.	2. Same.	2. Take out resistance in shunt field.
	3. Brushes not properly set.	3. Same.	3. Rock rushes back and forth till highest voltage is shown.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
3. Excessive current.	1. Too many lamps burning or motors running.	1. By too high reading of ammeter for capacity of machine.	1. Cut out necessary number of lamps or reduce motor current.
	2. In a motor, too much mechanical work being done by it.	2. By excessive sparking of motor brushes and too high reading of motor ammeter.	2. Reduce the load on the motor.
	3. In a dynamo, too much power being absorbed by motors in circuit.	3. By excessive sparking of dynamo brushes and too high reading of dynamo ammeter.	3. Reduce load on motor circuits. In this case, none of the motors may be doing too much work, but there may be too many in dynamo circuit.
	4. Short circuit; leak or ground in external circuit.	4. By excessive sparking of brushes, and heating of *whole* armature.	4. Locate and remove leaks or grounds.
	5. Short circuit in armature coil.	5. By heating of short-circuited coil more than the others.	5. Stop machine. Locate coil. If entirely burnt out, must be renewed.
	6. In a dynamo, by excessive friction in bearings of a motor or by motor armature striking pole pieces. In general any cause tending to slow motor.	6. By sparking of dynamo brushes. By sound of armature striking while running. By heating of motor bearings.	6. File away pole pieces of motor, or recenter armature. Clean and oil journals, or refit bearings.
	7. Grounds in armature. Two grounds to the core amount to a short circuit.	7. Same as 5.	7. Locate the grounds. Reinsulate the coils containing them.
4. Excessive sparking at brushes.	1. Excessive current; therefore due to any of the causes given under that head.	1. Same as given under "Excessive current."	1. Same as given under "Excessive current."
	2. Brushes improperly set.	2. By the sparking itself and heating of brushes.	2. Shift the brushes backwards or forwards till sparking is reduced to a minimum.
	3. Brushes make poor contact with commutator.	3. Same, and by sighting underneath between brushes and commutator.	3. Adjust, file or clean brushes until they rest evenly on commutator with light but even pressure.
	4. Rough, non-concentric commutator.	4. By the sparking. A rough commutator can be detected by lightly touching finger nail to it while running; an eccentric commutator by the regular rise and fall of the brushes.	4. Smooth commutator with fine file or fine sandpaper. If eccentricity is due to uneven wear of bearings, renew or reline them.
	5. "High" or "flat" bars in armature.	5. By the jumping or vibrations of the brushes.	5. Same as above, or turn down the commutator in lathe.
	6. Broken circuit in armature or commutator.	6. Commutator flashes, and nearest the break is cut and burnt. Flashing continues when armature is slowly turned.	6. Locate coil by drop of potential method. If in commutator, bridge over the break. If in armature coil, it must be renewed.
	7. Weak field magnetism, caused by broken circuit in field winding or short circuit in same; two or more grounds in windings; reversal of one or more field coils.	7. Dynamo fails to generate full E. M. F. If very weak, motor runs very slow.	7. Short circuits or grounds are easily located and remedied if external to the windings. If internal, faulty coil must be rewound or repaired if only grounded. A reversed coil will lower the voltage instead of increasing it, and it is remedied by reversing the connections.
	8. Unequal magnetism.	8. One brush sparks more than the other.	8. Only remedied by reshaping pole pieces.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
	9. Dirty commutator, causing brushes to vibrate, particularly if of carbon.	9. Flashing around commutator.	9. Clean commutator (methods given later).
	10. Poor brushes, especially if of high-resistance carbon hard blisters forming on them.	10. By ragged appearance of brushes around edges and formation of hard spots.	10. Renew brushes.
	11. Vibration, especially of brush holders, causing rapid vibration of brushes.	11. By a humming, singing sound of brushes.	11. Reduce cause of vibration or give the brushes a little greater pressure on commutator.
5. Heating of armature.	1. Excessive current through it and therefore due to any of the causes given under that head.	1. Same as given under "Excessive current."	1. Same as given under "Excessive current."
	2. Eddy currents in core.	2. Core becomes hotter than armature coils after running for a short time.	2. Only remedied by better design of core lamination.
	3. Conduction from other parts as from commutator or bearings, the heat being conveyed to armature. If from commutator, bars may be too small.	3. Other parts connected to armature, as commutator, shaft or bearings, hotter than the armature.	3. Locate source of heat by thermometer or feel by the hand, and correct it by cleaning and lubrication.
6. Heating of commutator.	1. Too great pressure of brushes, friction causing heat.	1. By feeling the commutator with the hand.	1. Reset brushes.
	2. Excessive sparking.	2. Same.	2. Discover the cause of sparking and correct it, according to the particular cause given under sparking.
	3. Excessive current.	3. Same.	3. Discover cause of excessive current and correct according to particular cause already given.
	4. Conduction from other parts.	4. Same.	4. If from bearings, lubricate or refit them.
7. Heating of field coils.	1. Excessive current in field circuit, due to short circuits or grounds.	1. Too hot to bear by the hand. If exceedingly hot, by smell of burning shellac or varnish or charring cotton.	1. Locate the particular coil in which fault lies and repair or rewind. Methods given later.
	2. Eddy currents in pole pieces, heat being conducted to the coils.	2. The pole pieces are hotter than the coils after a short run.	2. Only remedied by better design.
8. Heating of bearings.	1. Lack of lubrication.	1. By feeling with hand. Oil cups empty or feeding pipes clogged.	1. Fill oil cups; clean feeding pipes.
	2. Dirty or gritty bearings.	2. By feeling with hand.	2. Remove cap and thoroughly clean.
	3. Bearings out of line.	3. Unequal wear of bearings, and shaft will not turn freely by hand.	3. Bearings must be lined up or shells rebabbitted. If very serious, new bearings will have to be made.
	4. Rough or cut shaft.	4. Shaft will show the roughness in the bearings.	4. Turn down shaft in lathe, or if not too bad, reduce by filing.
	5. Shaft bent.	5. Unequal wear in bearings and armature will wobble. Very hard to move by hand.	5. Shafts can only be straightened by disconnecting from armature and reheating and reforging.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
9. Too low speed (referring to motors).	1. Too much load.	1. By speed indicator; heavy sparking, heating of all parts and bearings.	1. Decrease E. M. F. at terminals of motor or reduce the work to be done.
	2. Any of the causes given under "Heating of bearings" causing excessive friction.	2. Same, and same as given under "Heating of bearings."	2. Discover particular cause and remedy same as given under "Heating of bearings."
	3. Weak magnetic field and heavily loaded.	3. See cause 7, under "Excessive sparking."	3. Same as 7 under "Excessive sparking."
	4. Short circuit or grounds in armature.	4. By motor taking excessive current without load as shown by ammeter or heavy sparking and heating.	4. Same as under 5, "Excessive current."
	5. Too low voltage at terminals.	5. By motor voltmeter or speed indicator. By heavy sparking and heating.	5. By correcting line voltage.
10. Too high speed (referring to motors).	1. Too light load (in series motors).	1. By noticeable increased speed.	1. Increase load.
	2. Weak magnetism (if lightly loaded).	2. Same.	2. Same as 7 under heading "Excessive sparking."
	3. Too high voltage at terminals, due to high voltage of dynamo.	3. Same.	3. Correct line voltage by remedies 1 and 2 under "Too high voltage."
11. Dynamo fails to generate E. M. F.	1. Too weak residual magnetism, caused by a jar or reversal of current not sufficient to reverse magnetism.	1. Very little attraction by the pole pieces when tested with a piece of iron.	1. Send a current through field from a few cells or from a running dynamo.
	2. Short circuit within machine, or grounds in field windings.	2. Magnetism very weak.	2. Locate the grounds or short circuits and correct them.
	3. Reversed field coils.	3. All poles should have alternate magnetism; if a coil is reversed, it will show magnetism, but may not be of opposite polarity.	3. Make polarity opposite by reversing the connections of the coil. Each pole should be opposite to the one on each side of it.
	4. Series and shunt windings connected up opposite to each other.	4. Voltage falls as speed is increased, the external circuit being closed, showing that they are working against one another.	4. Reverse connections of either field, but not both.
	5. Brushes not properly placed.	5. Magnetism and E. M. F. increased by shifting the brushes.	5. Find central position by experiment or from drawings of connections.
	6. Open circuit due to broken wire, brushes not on commutator, switch open, connections loose, fuses burnt out.	6. If break or loose connection is in machine, magnetism will be very weak. If in external circuit, machine will show its regular magnetism and voltage at the terminals.	6. Make diligent search outside of machine. If in machine, test the circuits with magneto for continuity. Set up on all connections.
12. Motor fails to start.	1. Too much load.	1. No motion and fuse in circuit melts or circuit-breaker acts. See if motor runs all right when light.	1. If motor does not start at once, turn off current and search for cause. Reduce load on motor.
	2. Excessive friction, due to any causes given under heading "Heating of bearings."	2. Same, and motor hard to turn when not loaded, and with no current.	2. Remedies same as given under "Heating of bearings."

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
	3. Short circuit of field or armature or among connections.	3. Motor refuses to revolve, though shows signs of strong magnetism. Will turn easily by hand if unloaded and with no current. If current is very great, it is indication of short circuit. If fault is in field, magnetism will be weak.	3. If connections are made wrong, consult maker's diagram and correct them. Test for continuity and short circuits as given later.
	4. Open circuits due to field switch open, fuse melted, loose or broken connections, or some fault at generator.	4. Weak magnetism shows a loose connection in field circuit; no magnetism, that field switch is open. May be heavy current in armature. If there is no armature current there will be no spark at brushes when raised.	4. Turn current from motor, and search for cause of discontinuity; examine all switches, fuses and connections, tautening all. Test for continuity in machine circuits and repair broken or burnt-out coils.
13. Flickering of lamps.	1. Uneven running of engine, probably due to governor failing to properly function.	1. By flickering of lamps or vibration of voltmeter indicator.	1. Overhaul engine, especially governor.
	2. Loose connections, either on machine, switchboard or external circuit.	2. Same.	2. Examine all connections and see that they are firm and make good contact.

CHAPTER XXIII.

TESTS FOR AND LOCATION OF FAULTS.

Under the heading *Remedy* given in the table of the preceding chapter most of the remedies given are simple and explain themselves, as for instance: Remedy No. 1, under Fault No. 1, "slow the engine," which would of course be done by throttling down the steam; No. 2, "Introduce more resistance in shunt field," which would be done by a proper manipulation of the field regulator. Some, however, are but indicated, as No. 4, under Fault No. 3, "Locate and remove leaks or grounds," and it is the purpose of this chapter to enter a little more into the detail of the simple tests and the location of the faults.

Short Circuit in External Circuit.

This would be indicated by the melting of the fuses in that circuit, or possibly by the melting of the main fuses or by the opening of the circuit breakers. After determining the circuit on which the short is, an examination along it, if accessible, may lead to its location. If not, it can be tested for by the magneto or ohmmeter, by unscrewing all the lamps and opening the circuit at different points and ringing through both ways. Working from the switchboard, try the feeder first by disconnecting at the feeder junction box. By connecting the ohmmeter to the two ends, its resistance can be roughly measured; that is, it is either very high if the short is not there, or infinitely small if it is. By opening the circuit at various points, the short can be located within limits and further observation will accurately determine it.

The short circuit indicated by the melting of the circuit fuse would show that it was either on the feeder or mains; for each branch being protected, if it occurred in a branch it would only burn out the branch fuse. Short circuits in the external circuit

do usually occur in branches and particularly in portables, but then they are easily located as the branches are short. Most of them are due to moisture in the wiring accessories, or to the insulation being torn from portable wires, or burnt by hauling over hot coals or ashes.

Grounds in External Circuit.

A ground on an external circuit would be indicated by the ground detector, either of two kinds or both being connected to the mains.

Lamp Detector.—This, with its connection, is shown in Fig. 201. *A* represents a positive bus bar, and *B* a negative bus bar, from which lead circuits through the ship. 1 and 2 are two incandescent

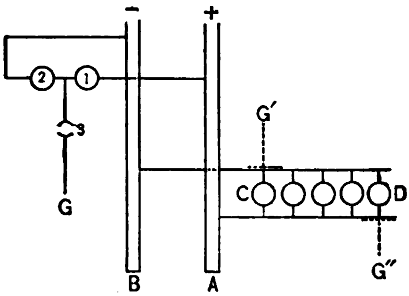

FIG. 201.—Connections of Lamp Ground Detector.

lamps connected in series across the bus bars. Between the lamps there is a connection to earth marked *G*, with a plug 3 to make the connection to earth complete. *C* and *D* are lamps on a circuit. If there are no grounds on the circuit, the lamps 1 and 2 will burn with equal brilliancy, but reduced candle-power, as with the same E. M. F. there is double the resistance, so only half the current flows through each lamp. If a ground occurs on the negative leg of the lamp circuit, the current will now flow from the + bar through 1, but will avoid the high resistance of 2, so will take a path through ground to the ground on the main as at *G′*, and thence to the — bar. The result of this is that 1 now has full current and will burn with full candle-power, while 2 will be extinguished. If it is only a slight ground, both lamps may burn but with unequal

brilliancy. If the ground was on the positive leg, the current would now avoid 1, taking the path through ground G'' to G through 2 to the — bar, and 2 would burn with increased brilliancy while 1 was lowered if not extinguished.

With several circuits closed from the bus bars and a ground appears, it becomes necessary to discover on which circuit it is, and this is done by cutting out the circuits, one at a time. On cutting out a circuit, and the ground disappears, it must have been on that circuit. On locating the circuit, keep that circuit in and cut out all the others. Then pull out the portables on that circuit one at a time, and if the ground disappears when a certain one is pulled out, the ground must have been on that particular portable, and it may then be sought and found.

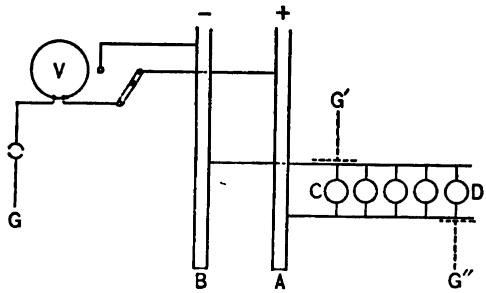

FIG. 202.—Connections of Voltmeter Ground Detector.

Grounds generally are due to moisture in the junction boxes or wiring accessories, or to the slipping of connections in lamp sockets, by which a bare wire may touch the outside shell which in turn may rest against some grounded conductor. A fruitful source of grounds is in the portable ventilating fans, the support frequently touching some exposed part of the leading wires.

Of course, grounds may occur in the mains, due to moisture rotting the insulation, and this can be tested for with the magneto, connecting one end to the main, the other to a ground and ringing through.

Voltmeter Detector.—Fig. 202 represents the typical connections for using a voltmeter to detect grounds. V is a double-reading

voltmeter with the zero in the middle of the scale, the indicator being deflected to the right or left, depending on the direction of the current through it. One terminal is connected to a contact piece fitted with a switch by which it may be connected to either bus bar of the generator, *A* or *B* and the other terminal is connected to a ground through a plug switch.

If connected as shown to the positive bar and there are no grounds on the negative side of any of the circuits, there will be no current through the voltmeter and no deflection, or the reading will be zero. If there are any grounds on the negative side, as at G', current will then flow from the + bar through the voltmeter to ground G to G' and to — bar. If it is dead ground, the full difference of potential between the bars will be indicated; if only a slight ground, the fall of potential, owing to the high resistance, will be very small.

Connected to the negative bar, any grounds on the positive side of the circuit will be detected, the current then being from the positive bar through the ground, as at G'', through ground G, through voltmeter to negative bar; the indicator now deflecting in an opposite direction to that of the first case.

The method of locating the particular circuit on which the ground exists is exactly the same as with the other ground detector, and also the same procedure is necessary to further locate the ground in the circuit.

The method of calculating the ground resistance is given on page 717.

Short Circuit in Armature.

A short circuit in the armature usually attracts attention by the smell of burning varnish or shellac. When this is discovered, the armature should be stopped at once, and felt all over by the hand, the short-circuited coil being much hotter than any of the other parts. A piece of iron held near a revolving armature with a short-circuited coil will be strongly affected once a revolution, as the coil passes the iron. If a large part of the armature is short-circuited, it is not so easy to distinguish the parts by the heat, so some fall of potential method is resorted to.

One way is to pass a strong current through opposite commutator bars and measure the difference of potential between the points where contact is made with the commutator. Then connect one terminal of a portable voltmeter to one connection and the other terminal to the different bars of the commutator. If the armature is sound, there should be the same fall of potential from the leading-in point to bars each side equally distant from it. In this way the fall of potential from bar to bar may be determined, and the fall should be regular, and if between any two bars there is a smaller fall of potential than the average it shows the presence of a small resistance, or probably the short-circuited coil.

A short-circuited armature coil can only be remedied by rewinding.

Short Circuit in Field.

Usually a short circuit is confined to the windings of one spool; the effect of which will be to cause weak magnetism in the short-circuited coil, and a piece of iron held at an equal distance between poles will be more strongly attracted by the good one than by the weak.

A short-circuited coil will cause the resistance of the total field to be much reduced, and this can be detected by roughly measuring with the bridge. The fall of potential method can be used to detect the spool in which the short circuit is.

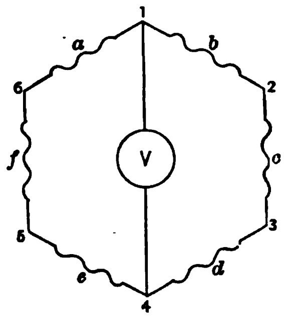

FIG. 203.—Testing for Short Circuit of Field Windings.

Suppose the coils are represented by *a, b, c, d, e* and *f*, in Fig. 203, and a source of current is connected to 1 and 4. Measure the fall of potential between 1 and 4, between 1 and 6, 1 and 5, 1 and 2, 1 and 3. The fall between 1 and 6 should be the same as between 1 and 2; between 1 and 5 the same as between 1 and 3, and consequently between 5 and 6, and 4 and 5 the same as between 2 and 3, and 3 and 4. If this symmetry does not exist between any two coils, then that coil must be the short-circuited one. The short-circuited coil should be cooler than the others.

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Grounds in Armature.

A single ground in an armature is not a source of trouble, but two or more, especially in the same coil, become a short circuit with its evil effects. The particular coil in which grounds to the core exist may be determined by connecting all the commutator bars together by wrapping them with a conductor and passing a current through this wire, taking the other leading wire to the iron core. Current then flows through the armature coils through the grounds to the iron core, thus magnetizing the coil in the vicinity of the grounds, and these points can be detected by a small compass needle moved around the armature.

Grounds in Field.

The effect of grounds in the field is to short circuit a coil, and they can be detected and located in the same manner as a short-circuited coil.

Fracture in Armature.

This can usually be detected by violent flashing on the commutator, the commutator bar nearest the break being burnt or cut. A bad case of high or low bars may produce this same flashing, but if produced by this cause, it will disappear when the armature is slowly revolved, which will not be the case if caused by a fracture.

A fracture can be detected by a magneto which will not ring through a broken circuit, and can only be found by fall of potential, the same as in detecting a short circuit in armature. A voltmeter, one terminal connected to the leading-in wire, will not indicate when connected to adjoining bars until it has passed the break, for up to that time there has been no complete circuit, but when one terminal is on one side of the break and the other terminal on the other, the circuit is complete, and the fall is indicated. The fractured coil must lie between the commutator bars where one does not indicate and the adjoining one does.

In case of armature-coil fracture no particular coil will be heated more than another; if anything, the fractured coil being cooler than the others, as the current does not flow through it.

Fracture in Field Winding.

If there is a complete fracture of both the series and shunt windings in a compound generator, it will probably refuse to excite. The test for fracture can be made with the magneto, and the coil containing the fracture detected by fall of potential.

Suppose in Fig. 204 *a, b, c, d, e* and *f* represented the field coils in a six-pole machine, and that they were connected with a source of current at the terminals marked + and —. If there was a break in a coil, say in *e*, a voltmeter connected to 7 and 6 would not indicate; nor would it if connected to 7 and 5, but if connected to 7 and 4, it would indicate, the circuit now being complete, showing the voltmeter had bridged over the break in coil *e*. If there was also a break in *d*, connection between 7 and 4 would show no current, but would between 7 and 3. Connection between 3 and 4 would show no indication if there was a break in both *d* and *e*, but would if it was only in *d* alone. If breaks were in both *d* and *e* connection between 3 and 5 would show current, and in this way it can be determined absolutely in which coils breaks occur.

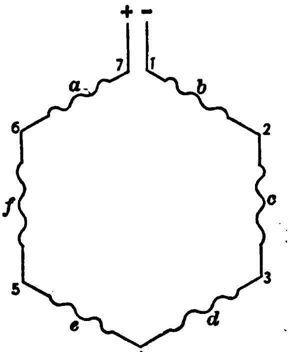


FIG. 204.—Testing for Fracture in Field Winding.

If the fracture is outside, it is comparatively easy to repair, but if internal, the coil would probably have to be rewound. Excessive vibration sometimes carries away the connections between the spools and they are apt to break off under the outside layers.

To Test for Magnetism.

Magnetism can be detected by any magnetic material, such as a piece of iron or steel or iron tool, as screw-driver or knife, being approached to a supposed magnet. Magnetism will be shown by the iron held in the hand being attracted, requiring at times considerable force to hold it away from the magnet. To detect very weak magnetism a small compass needle is used, being deflected by the very faintest trace of magnetism.

The polarity may be determined by the compass needle, by remembering that like poles repel and unlike attract.

To Test for Speed.

This is done by the use of a tachometer, which by applying its shaft to the shaft of the rotating armature indicates at once the number of revolutions. Or a speed indicator is applied to the end of the armature shaft and the number of revolutions made in a given time is counted.

To Test for Heat.

Under the table of faults, by far the greatest number of faults fall under the general head of heating, such as heating of armature, heating of commutator, heating of field coils, heating of bearings, and even the faults due to excessive current and excessive sparking are mostly faults due to the heat produced by them.

Remarks on Heating.

The expression excessive heat is one that requires a little more definite limits, for what might seem excessive to one might not be to another.

The amount of heat that is allowed in the armature coils and field windings above the temperature of the surrounding air is limited by specifications, but the degree of heat that is positively injurious is easily determined by feeling the various parts. If the heat in any part of the winding is greater than the hand can stand for a few seconds, then it is higher than a safe limit. If the hand can stand the heat for two or three minutes, it is usually not considered excessive. If there are any signs of smoke or smell of varnish or shellac or rubber, the temperature is far too high. The only way to cool heated parts is to stop the machine, except possibly in the case of bearings, where water might be used.

For accurate results as to temperature, the thermometer should be used on the parts, the bulb covered with waste and the highest reading recorded taken. To find the heat or temperature in the field windings, calculations should be made from the cold and hot

resistances by knowing the per cent increase per degree rise of temperature.

In considering the heat in any portion of a machine, it is very necessary to locate the exact source of the heat. Every or any hot part may not be the real cause, but the heat may have been conducted there from other places. A hot bearing might make a hot commutator or armature and vice versa. In locating heat troubles the very hottest parts should be sought, as they are very likely to be the source of trouble. If a certain part heats under certain conditions, it is likely it will do so again under the same conditions. To discover the parts that heat first, it is better to start with the machine absolutely cool in all its parts, and then after a short run to feel all over for the hot parts, for in a short run, there will not be time for the heat formed to be conducted to other parts. After a long run, only general temperatures can be obtained, but it cannot be told with certainty just what the source of heat is, for there is a general distribution all over the machine.

Uses of Electric Fault Finder.

The following tests are given in the instructions furnished with the instrument and refer particularly to armature tests. Reference should be made to Fig. 180.

Test No. 1. To Discover Leaks.—Screw down Switch No. 1 and unscrew switches Nos. 2 and 3. Pull up battery switch. Adjust rheostat until sound is as loud as the ear can comfortably endure with the test terminals in contact. With the test terminals separated, there will be no sound in receiver. Place one test terminal on armature shaft, and other test terminal on commutator. If there is a leak, a sound will be heard. With one test terminal held tightly in each hand, the loudness of sound indicates a resistance of 10,000 ohms or more.

Test No. 2. To Locate Grounds.—Screw down switches Nos. 2 and 3 and unscrew Switch No. 1. Pull up battery switch. Adjust rheostat until there is no sound in receiver with the test terminals in contact. Place one test terminal on armature shaft and pass other test terminal around the commutator. If there is a grounded coil or bar, sound will decrease as grounded coil or bar is ap-

proached, and will almost or totally disappear when grounded coil or bar is reached. If in test No. 1 sound is so loud that a ground is indicated, and, if in test No. 2, sound on all commutator bars is the same and very faint, it shows that the entire commutator is grounded.

Test No. 3. To Locate Short Circuits.—Adjust the fault finder as in test No. 2. Place one test terminal on any commutator bar and the other test terminal on the next bar. Follow around the commutator keeping the test terminals on adjacent bars (the handles are flattened so this can be done with one hand after the spacing is adjusted). When the short circuit is found, sound in the receiver will be gone or very faint. If the sound is loud, an open circuit exists and should be found as per test No. 5. The other end of the coil may be found as per test No. 4.

Test No. 4. To Locate Coil Ends.—Adjust the fault finder as in test No. 2. Mark a bar on the commutator and place one of the test terminals on it. Then move the other test terminal around the commutator and when the other end of the coil is reached, there will be very little sound in the receiver. Should the coil be open, the sound will be very loud.

Test No. 5. To Locate Open Circuits.—Adjust the fault finder as in test No. 2. Mark a bar on the commutator and place one of the test terminals on it. Next find the other end of the coil as per test No. 4. Then pass both test terminals from bar to bar in the same direction around the commutator, being careful to stay at the ends of each coil. When the open circuit is reached, the sound in the receiver will be the loudest.

The following instructions apply to field coil testing:

Test No. 6. To Locate Grounds.—If in test No. 1 a loud sound is obtained and the armature and field are connected, the ground may be in either armature or field. Disconnect field from armature and test each separately. If field is grounded, test separately each field coil, thus determining which coil or coils are grounded. Remove field coil and repair. When coil is removed, connect one test terminal with each end of coil and determine if coil is open. If coil is open, find open circuited layer as per test No. 8. While coil is removed, also test for short circuits as per test No. 7.

Test No. 7. To Locate Short Circuits.—Adjust fault finder as in test No. 2. Strip insulation about one-half inch wide, on end of coil exposing each layer. Place one test terminal on exposed wire of outside layer and place other test terminal on exposed wire of next layer. Next, advance second test terminal one layer, when the sound will be louder. Continue this way and the sound will increase for each layer tested. When the short circuited layer is reached, the sound, instead of increasing, will remain the same.

Test No. 8. To Locate Open Circuits.—Adjust fault finder as in test No. 2. Proceed as in test No. 7. When open circuited layer is reached, sound will be loudest. Tests No. 7 and No. 8, locating the trouble exactly, will give information sufficient to determine whether the coil should be scrapped or repaired.

The above tests on dynamo electric machines will suggest numerous other tests on electric circuits in general, which may be made with the electric fault finder. For instance, by using the fault finder as in test No. 1, all the testing usually done by a magneto may be performed by one man, with much greater accuracy, and over a wider range of resistance, than with a magneto. In general, when using the fault finder for exploration work—which is the kind of testing usually done with a magneto—adjust the fault finder as per test No. 1. When a faulty low resistance circuit is to be located among a number of low resistance circuits, adjust the fault finder as in test No. 2.

CHAPTER XXIV.

TELEPHONES.

The underlying principle of the telephone is *the increase or decrease of intensity of an unbroken electric current,* and in order to transmit sounds of the voice over an electric conductor it is necessary that a current be caused to flow in the conductor and that the intensity of the current is in accord with the vibrating movements of the sound-producing body.

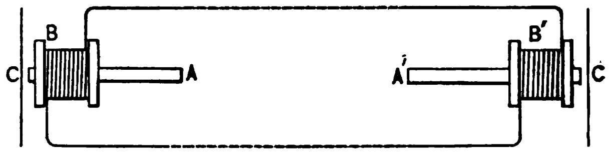


FIG. 205.—Simple Telephone Connection.

The early invention of the telephone is illustrated in Fig. 205. In its simplest form it consists of a *permanent bar magnet* A, A' at each end, with one end of each surrounded by a coil of fine wire B, B' in series with the line connecting the stations. A soft-iron diaphragm C, C' is mounted close to one end of each of the magnets. When a sound is made in front of the diaphragm, it vibrates in exact accordance with the sound waves striking against it. The vibrations produced by the voice are transmitted by the air to the diaphragm and this latter vibrates back and forth in front of the magnet. These vibrations of the diaphragm produce backward and forward movements of the lines of force which pass into the diaphragm and which are due to the permanent magnet. The magnetic field between the pole of the magnet and the diaphragm is shown in Fig. 206.

Some of these lines of force cut across the coil B, first in one direction and then in the other and induce currents in it. These

very feeble currents are transmitted by the line to the other end, where those in one direction pass around B' in such a direction as to *increase* the strength of the permanent magnet A', and the attraction which it exerts on the diaphragm C is thus increased. Opposite currents pass around B' in the reverse direction and *weaken* the magnet A', diminishing the attraction on C'. When C moves in one direction, C' moves in one direction and when C moves in the opposite direction, C' reverses its direction. One therefore vibrates in unison with the other and the receiver sends out waves exactly like those that fell upon the sender, and a sound made at C is reproduced at C'.

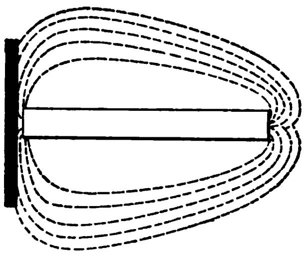


FIG. 206.—Magnetic Field at Telephone Receiver.

As long as sound waves impinge against C, alternating currents of varying intensities pass over the line and increase or decrease the strength of the permanent magnets. No battery is used in this circuit, the only currents being the induced currents caused by the lines of force cutting across the coils on the ends of the magnets, and which are so feeble that only the most sensitive instruments can detect them.

Variable Resistance Transmitters.

The source of the induced currents in the simple telephone circuit above described is due to the energy of the sound waves, and in consequence of which they are very feeble and such a transmitter could have no practical value except for very short distances. The early experiments to secure a practical transmitter were along the lines of causing variation in the strength of current produced by some outside means, the variation always remaining in accordance with the movements of the diaphragm. A battery was used and the transmitter was so designed as to cause variation in its current strength by changing the resistance in the battery circuit.

Edison Transmitter.—One of the first practical transmitters was devised by Edison and carbon was the substance by which the resistance of the circuit was varied. Carbon pieces in contact vary in their electrical resistance according to the pressure with which they are held together. The first type consisted of a platinum disc secured to the diaphragm bearing against a button of compressed plumbago. The circuit was completed through this contact which was varied by greater or less pressure on the plumbago button caused by variations in the sound waves striking the diaphragm. This change of resistance caused variations in the current that passed over the line to the receiver.

Hunning's Transmitter.—In Hunning's receiver the variable resistance medium consists of a quantity of finely-divided carbon granules held between two conducting plates, and through which the battery current flows. This form has a large number of imperfect contacts and the change in resistance is caused by the change in the pressure with which the granules are held together. The diaphragm is so arranged as to press more or less against these carbon particles and thereby produce changes in resistance which cause currents of varying intensities in the line.

Nearly all successful transmitters are modifications of this type.

Hughes' Microphone.—This type of sound transmitter or sound multiplier depends on the variations in resistance of an electric circuit caused by *loose contact* of electrodes. The elementary principles are illustrated in Fig. 207.

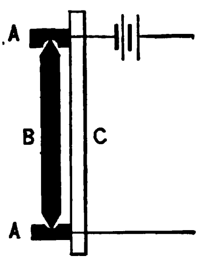


FIG. 207.—Hughes' Microphone.

C is a sounding board holding two cup-shaped contacts *A*, *A* of carbon, between which lightly rests a carbon strip *B*, which makes imperfect contact at *A*, *A*. These are connected to a battery in which a receiving instrument is included. The slightest noise, imperceptible to the unaided ear, sets up vibrations which disturb the contact of *A* and *B*, and so sets up variable currents in the line which are reproduced in the receiver with great distinctness. The clearness and distinctness of the sounds vary with the pressure, and as this is gradually increased,

the sounds become weaker, though always clear, until when the contact is perfect the sound ceases.

This indicates that it is not the resistance of the carbon itself which changes under pressure, but the change of resistance is caused by the imperfect contact at the carbon electrodes.

Of the different theories advanced for the explanation of the change of resistance of carbon under pressure, the most probable one is that the change of resistance is due to the variation of the area of contact, and in the granular form it is the variation in the number of granules in contact. An increase of pressure increases the area of contact, lowers the resistance and allows greater current to flow, while a decrease of pressure produces the opposite effect.

Carbon Transmitters.

Of the variable resistance transmitters mentioned in the preceding section, those made on the principle of the Hunning's transmitter have been the most successful, for no substitute for carbon as the variable resistance medium has been discovered. Carbon has all the properties requisite for telephonic or microphonic work; it produces change of resistance by surface contact; can be easily made into the desired form; it does not oxide or corrode; it is abundant and cheap.

The form of transmitter almost universally used in this country in the early days of telephones was the **Blake transmitter.** In this a platinum pin is pressed by a light spring against a polished plug of *hard* carbon, forming an imperfect, delicate contact through which the current flows. This mechanism is mounted behind the usual disc which takes up the vibration of the voice, and greater or less pressure is brought on the contact of the platinum pin and carbon, the varying resistance producing the requisite varying intensity of the line current.

This transmitter is very delicate and transmits the quality of the voice in an excellent manner, but it lacks in power.

Many forms of the carbon granular type have been made, and although all present peculiarities, the general principle of construction is the same, and a description of one will render clear the action of the others. The type of transmitter in general use by the

American Bell Telephone Company is known as the **White transmitter**, and is spoken of as a "solid-back" type. Its general construction is shown in Fig. 208.

The front, *A*, is of metal, forming with the back, *B*, a complete metallic casing for the working parts of the instrument. The diaphragm, *D*, is of aluminum, held by a soft-rubber ring *E*, and

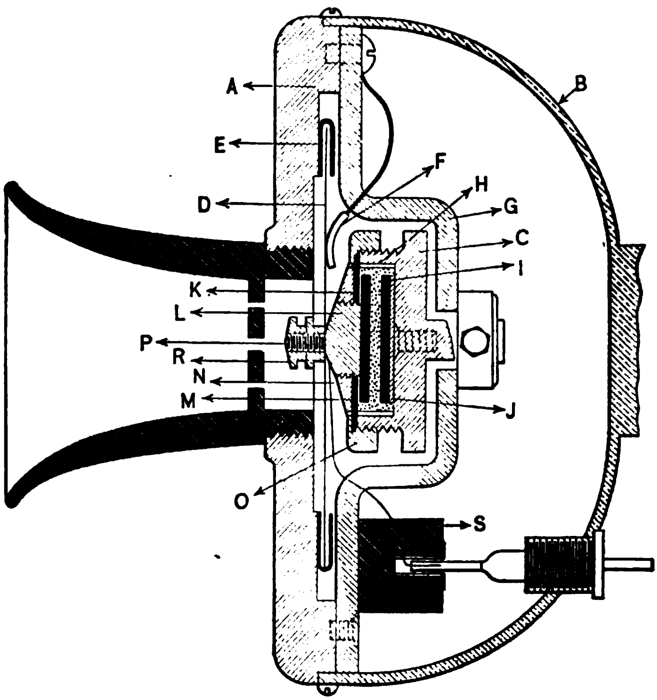


FIG. 208.—White "Solid-Back" Transmitter.

against which are held two damping springs, *F*, only one of which is shown. *C* is a metallic block, hollowed out to form an enclosure for the electrodes, and is held rigidly in place by a supporting bridge, which is secured to the metal front piece. The inner circular wall of *C* is lined with paper, and screw-threaded into its inner face is a metallic piece, *I*, against which rests the back electrode of carbon, *J*. The front electrode, also of carbon, *K*, is

carried on a metallic piece, *L*. On the flange of the piece, *L*, is carried a mica washer, *M*, held in place by the screw nut, *N*, and the washer is of sufficient diameter to cover the cavity in the block, *C*, when the front electrode is in place.

The space between the two electrodes is filled with granular carbon, and as the electrodes are slightly smaller in diameter than the cavity, the space around them is also filled with the granules. There is sufficient space left to allow for the expansion of the granules due to the heat of the current, and this form allows a large current without undue heating.

When the carbon granules have been put in the cavity and the front electrode is in position, the mica washer is slipped in and the nut, *N*, is screwed in place; after which the cap, *O*, is screwed on, binding the washer firmly against the face of the block, *C*, and confining the granules in the cavity.

The screw-threaded portion, *P*, of the piece, *L*, passes through a hole in the center of the diaphragm and is held in place by the nuts, *R*. The vibration of the diaphragm is conveyed to the front electrode, which can move against the elasticity of the mica washer, while the back electrode is firmly held, and thus more or less pressure is brought to bear on the carbon granules between them.

The back electrode is in metallic connection with the back of the instrument which forms one terminal, while the other terminal is mounted on an insulating block, *S*, and is connected to the front electrode by a flexible connecting wire.

Receivers.

The typical form of telephone receiver is shown in the elementary sketch in Fig. 205, and it might be said that the receivers used in modern practice are but developments of the single permanent magnet, with one end wound with a coil of fine wire.

In the first days of telephone work, the receivers were of the single-pole type. In general they consisted of a compound bar magnet formed of two pairs of magnetized steel bars, placed with their like poles together. Between the bars at one end is clamped a soft-iron pole piece, and at the other a similarly-shaped iron block. The soft-iron pole piece forms the core of a coil of wire

which is slipped over it, and near this coil is secured the vibrating diaphragm. The whole is mounted in a conveniently-shaped rubber shell, formed of two pieces, one enclosing the magnets, and the other screwing into it and holding the diaphragm in place. Heavy leading-in wires run from the coil along the inside of the rubber shell to terminal pieces at the bottom which project through and form outside terminals to which the line wires are connected.

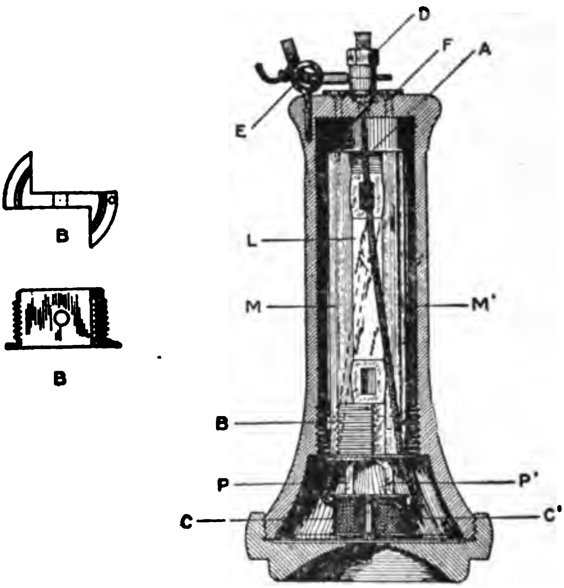


FIG. 209.—Bell Telephone Receiver.

Bipolar Receivers.—The object of bipolar receivers is to strengthen the field in which the diaphragm vibrates by presenting both poles to the diaphragm, and the lines of force are concentrated near the point where they are most effective. There have been as many different forms of receivers made as transmitters, but the governing principle remains the same, and the construction of one successful receiver will illustrate all the principal points. Such a form used by the Bell Companies is shown in Fig. 209.

In Fig. 209 are shown two magnets, M and M', secured at one

end by screws through an iron tail block, *A*, and at the other end by a threaded brass block, *B*. The pole pieces, *P*, *P'*, carry the coils, *C*, *C'*, and are clamped between the pole end of the magnets and the block, *B*. This block screws into a threaded portion in the rubber body of the shell and by turning it the magnet poles are moved nearer to or farther from the diaphragm, and after once being adjusted, it is held by a pin through the shell. The binding posts, *D*, are fitted with lock-nuts and there is an eyelet, *E*, fitted to take the strain cord, so no strain will come on the terminals if the receiver should happen to fall. In order to give sufficient weight to properly work the hook switch, a lead weight, *L*, is clamped between the magnets. The diaphragm is secured between the two pieces of rubber shell.

Watch-Case Receivers.—In some classes of work it is necessary to hold the receiver constantly at the ear, so that the hands may be free, as in wireless telegraphy, fire control or switchboard work. For such purposes a special form of receiver that can be held in place over the ears has been devised and from its shape and small weight it has been called the "watch-case" or "head" receiver.

These are fitted with either one or two receivers, to cover either one ear or both, and are made with straps to go over or around the head to hold them securely in place.

The permanent magnets are circular in shape and of the ring type and are cross magnetized to produce poles on opposite sides of their circumferences. Circular pole pieces which carry the coils are secured to the ring magnet and their pole faces rest close to the diaphragm as in the ordinary receivers. The working mechanism is mounted in a hard-rubber shell and the diaphragm is secured between this shell and the ear piece.

Use of Induction Coils.

The first practice in connecting telephonic instruments was to connect the transmitter, the receiver and battery at one station directly in the line leading to the other station, considering for the present but two stations. The change in resistance of the whole line, whereby currents of varying intensities were produced to actuate the receivers was caused by the change of resistance in the

transmitter. In case of a long line this change of resistance was very small in comparison to the whole resistance and the currents were consequently very feeble. To remedy this difficulty, Edison proposed to use an induction coil with the primary in the circuit of the transmitter.

The connection of the induction coil is shown in Fig. 210.

T represents the transmitter in series with the battery B and the primary I' of the induction coil, I'' the secondary of the induction coil is in series with the receiver R and the line L_1L_2. The transmitter in this connection is operating in the low resistance of the primary circuit, rather than over the resistance of the whole line,

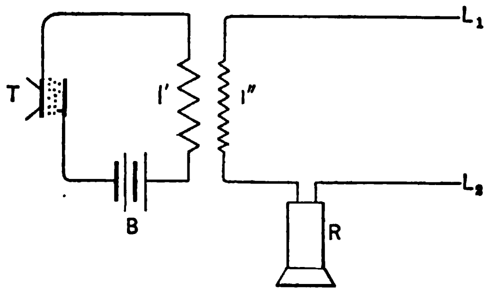


FIG. 210.—Connection of Telephone Induction Coil.

and any change of resistance caused by the transmitter bears a much larger ratio to the resistance of the primary circuit than it does to the resistance of the whole line, consequently, for the same voltage, the changes of current will be proportionately larger in the primary and the induced currents in the secondary that pass over the line will be proportionately greater. The fluctuations of current produced by the induction coil are many times greater than could be produced by the transmitter alone.

Another advantage of the induction coil is that the primary being of few turns while the secondary is of many, the induced currents in the secondary have a very high voltage as compared to those in the primary, and transmission can be effected over much greater length of line and over much higher resistance than if the transmitter was used alone.

Calling Apparatus.

Before conversation can be carried on between points, there must be some means adopted by which a person at one station can attract attention at the other. Ordinary vibrating call bells or buzzers are used, fitted with separate lines and batteries, or the talking battery may be used over separate lines, or over the talking lines. For long distances, ordinary batteries will not furnish sufficient current to operate call bells, and in some cases, they have been used with induction coils, using the high voltage of the secondary windings to furnish the desired current.

In many systems, especially in that known as the local-battery system, a form of generator is used that is very similar to the magneto shown in Fig. 171, Chapter XX. This furnishes alternating currents of high voltage and actuates a vibrating bell at the called station.

In central stations using the "local-battery" system attention is called by the ringing of the call bell, and at the same time by the dropping of a shutter which indicates the number of the calling station.

In the "common-battery" system, the attention of the operator is called by the lighting of an incandescent lamp by the operation of the caller removing the receiver from the hook.

Local-Battery System.

This system, as its name implies, has a local battery at each station to furnish the talking current. The system is classified under two heads, **series** and **bridging**. The series system is used when a number of instruments are used in series on the same circuit, and the bridging system where the instruments are placed in multiple or bridged across the line. This last is the more common practice.

The calling and talking apparatus operate over the same line, and when the circuit is complete for one operation it must be open for the other and vice versa, and means must be provided for effecting this result. It is now universally accomplished by a switch actuated by the weight of the receiver, and when the receiver is hanging in its provided place, the talking circuit is cut out and the calling circuit is closed ready to operate for calling.

At each station in this system there must be provided the transmitter, receiver, induction coil, battery, switch, bell and generator. It is customary to place the generator, the bell, the switch and the induction coil in one box and the battery in a separate box.

The connections for a complete station on the bridging system is shown in Fig. 211.

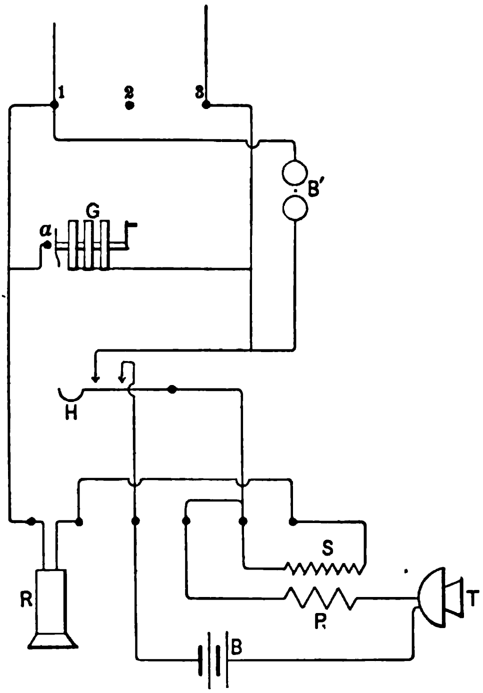


FIG. 211.—Bridging Circuit.

In Fig. 340, *R* is the receiver; *T*, the transmitter; *B*, the battery; *P*, the primary of the induction coil; *S*, the secondary; *B'*, the bell; *G*, the generator; *H*, the hook switch, and 1, 2, 3, the terminals. The line terminals are connected to 1 and 3. The position of the hook switch, *H*, shown, is accomplished by hanging the receiver on it. In this position it will be seen that the talking battery is cut out and the circuit open, and the station is ready for a call. The

bell, B', is bridged directly across the line and incoming current finds but the one open circuit, that through the bell. The generator, G, is across the line, and its circuit is broken at a, but is made by the operation of turning the handle of the generator.

To call from this station, it is only necessary to operate the generator and current goes over the line past the bell terminals to the called station, the talking circuit being open. After being called; to talk, it is only necessary to lift the receiver from the hook switch and the battery terminals are connected through the transmitter and the primary of the induction coil. The terminals of the secondary are connected by the same operation to the line through the receiver.

The above description is that of an ordinary "wall set" connected on the multiple or bridge system. In the series system, the call bell is connected to the line when the receiver is on the hook, and is cut out when the receiver is lifted clear.

The connections for "desk sets" are practically the same as for the "wall sets," different dispositions being made of the induction coil, calling apparatus and battery.

Common-Battery System.

In the Local-Battery System, it is usual to make use of the magneto for calling central, but in the Common-Battery System signals are made by simply lifting the receiver from the hook and replacing it. In some types of signals, lifting the receiver has the effect of lifting a target within sight of the operator and holds the signal displayed until the receiver is hung again on the hook, when the target drops in place, either by its own weight or under the action of a spring.

The modern method is to use a small incandescent lamp which is illuminated as soon as the hook is released by taking off the receiver. To signal any station from central requires some kind of a sound apparatus to attract attention, and current to operate this must come through the same line as the talking circuit. The signal apparatus must be in a condition to be energized at any time while the receiver is on the hook and consequently when there is no connection between the two sides of the line.

An alternating current provides the necessary solution of this problem, as it does not require a continuous metallic circuit, and it is practically done by interposing a condenser in series with the bell across the line. This bell is energized by a magneto at the central station, the condenser allowing the alternating current produced to pass through it, while it acts to keep the current of the common battery at central open.

The illuminating lamp at central may be placed either directly in series with the common battery and the line, or in a relay circuit, which is thrown in only when the battery circuit is established by lifting the receiver. In the former case, the resistance of the signal-bell magnets is sufficient to prevent enough current from flowing to illuminate the lamp, but when the receiver is

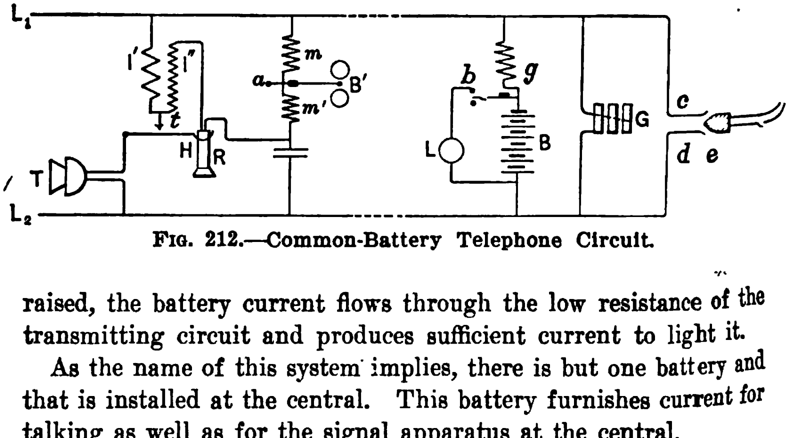


FIG. 212.—Common-Battery Telephone Circuit.

raised, the battery current flows through the low resistance of the transmitting circuit and produces sufficient current to light it.

As the name of this system implies, there is but one battery and that is installed at the central. This battery furnishes current for talking as well as for the signal apparatus at the central.

The complete connections from a station to central are illustrated in Fig. 212.

The station on the left (Fig. 212) represents one station and that on the right, the central, connected by the two lines L_1 and L_2. A battery, B, of about 25 volts is kept connected at central to all the lines entering it, but no current flows from this battery as long as the receivers, R, are on their hooks, H. In that condition there is no circuit for the direct current of this battery, as the condenser, C, acts as an infinite resistance to it. If central wishes to call the station, it is only necessary to throw upon the line an alternating

circuit which passes into and out, or through the condenser. This is done by turning the handle of the magneto generator, G. As the alternating current flows through the coils of the bell magnets, m and m', the armature which is pivoted at a is drawn first towards m and then towards m', vibrating back and forth between the bells B', producing a ringing sound.

If the station wishes to call central, it is only necessary to lift the receiver R from the hook H. This closes the line circuit at t and allows current from the battery B to flow in the line through the transmitter. At the same time the current flowing energizes the electromagnet g, and its armature is attracted, closing the lamp circuit containing the lamp L at b. This illuminated lamp attracts attention of the operator who moves a switch to connect the central telephone to the calling station. As the calling station talks into the transmitter the strength of the battery current through the primary I' of the induction coil is varied by the varying pressure produced on the diaphragm of the transmitter. These variations induce in the secondary I'' of the induction coil the talking currents which pass over the line to the receiver of the operator. By this arrangement the primary and secondary currents pass over the same line but it does not interfere with the distinctness of speech.

When the operator finds what station is required, it is rung up and connection is made with it by a plug e containing a flexible cord, which is pushed into the contacts c and d. When the conversation is over the receiver is replaced on the hook which breaks the battery circuit and the lamp at central is extinguished. The operator then disconnects the two stations.

Switchboards.

Telephone switchboards are used for interconnecting telephone lines centering at a common point. The two general systems, Local-Battery or Magneto System and Central-Battery System require each a different arrangement of the talking and calling apparatus, though they contain certain parts that are common to each.

The terminals of all lines entering the exchange at the switch-

board are secured to **spring jacks**, by which the line may be connected to another by the insertion of a plug in the jack. These jacks are small switch sockets, and so arranged that both lines of the metallic circuit are continued in a flexible cord by the insertion of the plug. This is generally accomplished as follows and can be seen in Fig. 213. One terminal of the line is secured to a circular ring which forms the socket for the plug, and the other terminal ends in a spring contact. The plug is so constructed that its tip end makes contact with the spring contact of the line terminal while the body of the plug forms a sleeve and makes contact with the ring socket. The tip and sleeve of the plug are insulated from each other and the terminals of the flexible cord are secured, one to each.

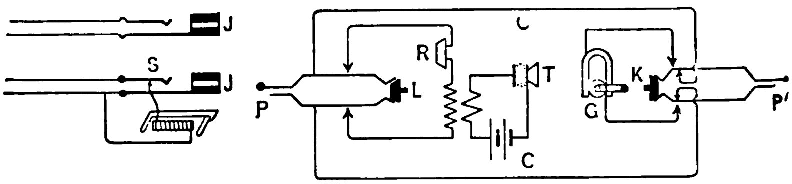


FIG. 213.—Magneto Switchboard.

Cord circuits are common to switchboards used with the two principal systems. Ordinarily it is a term which refers to two plugs with the connecting flexible wire and the necessary calling and talking apparatus by which an operator may answer a call or complete a connection with any line. In magneto switchboards a cord circuit consists of two plugs adapted to fit the spring jacks, with the connecting cord; a listening key by which the operator can connect the central talking apparatus so that conversation may be had with either one or both communicating stations, and a ringing key by which the central magneto is connected to one of the plugs and the station whose jack is plugged may be called.

Magneto Switchboard.—The essential parts of a magneto switchboard are shown in Fig. 213. The lines on the left are those from distant stations and all end in the spring jacks, *J, J*. In the lower line is shown the calling apparatus with which each line is provided. It consists of an electromagnet energized by currents produced by

the generator at a calling station, which pass over the line and around the electromagnet. When the core becomes magnetized, it attracts its armature, shown to the left, and which is pivoted at the upper end and connected to the rod above the magnet. This rod ordinarily holds in place the front target which is hinged at its lower end. As the armature is attracted, the target is released and drops, exposing the number of the calling station.

The cord circuit consists of the two plugs, P and P', fitted as above described with tip and sleeve contacts to engage the spring jacks, J, the flexible cord, C, C, and the talking and calling apparatus. The general operation of calling and talking would be as follows: Suppose the lower station calls by turning his magneto handle. This throws an alternating current on the line and on the electromagnet at central becoming magnetized, the armature is attracted and the target drops. On seeing the number of the calling station, the operator pushes the plug, P, into the spring jack, J, and presses the listening key, L. This connects the operators talking circuit in series with the line circuit of the calling station and disconnects the signal circuit, by the tip of the plug raising the spring contact, S. On finding the number of the station desired, the operator pushes the plug, P', in the jack of the desired number and presses the calling key, K. This connects the central generator, G, to the line of the desired station, and on turning the handle of the generator, current is sent over the line and rings the bell at the desired station. When the calling key is depressed, the talking circuit is cut out, by means of the spring contacts shown at K, so the alternating current of the generator cannot go over the line of the original calling station. When the desired station is obtained the ringing key is raised and the two stations are now connected for conversation.

There is usually fitted, in addition, another electromagnet across the cords circuit, C, C, which is actuated by current from either station while the jacks are still plugged to indicate that the conversation is finished.

Common-Battery Switchboard.—The circuits of a modern common-battery switchboard as developed by the Western Electric Company are shown in Fig. 214. The leads L_1 and L_2 (heavy lines)

are connected to a station, and another station, which could be shown on the right would be exactly similar. The **cord circuit** for the switchboard embraces all the portion between the plugs *P* and *P'*, and in addition the switchboard also embraces the circuit shown on the left under the heavy lines L_1L_2 of the calling station. A

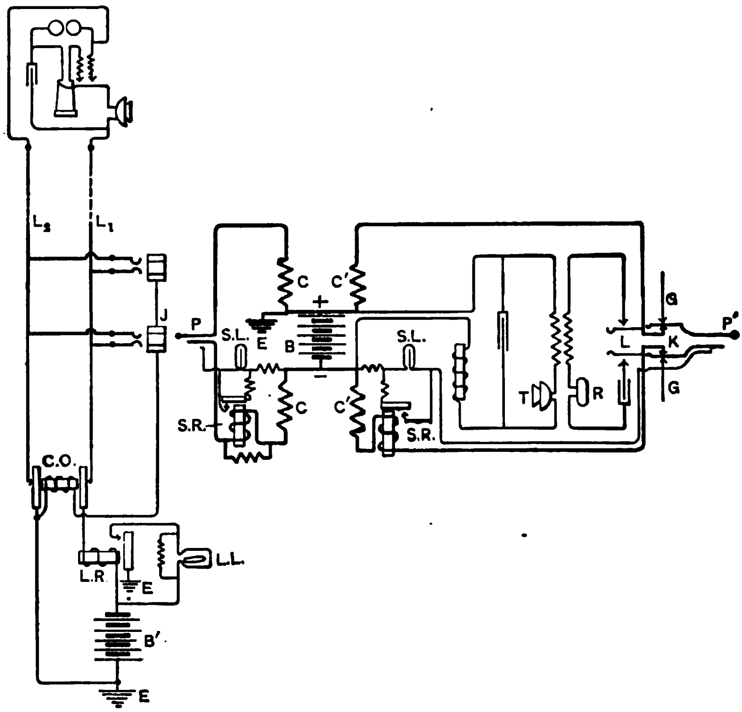


FIG. 214.—**Elements of Common-Battery Switchboard. Western Elec. Co.**

station on the right, or called station, would have an exactly similar equipment at the switchboard.

To signal the operator, the calling station takes the receiver from the hook. Circuit is then completed from the battery *B'* through the **line relay,** *LR,* through the primary of the induction coil at the calling station and the two armatures of the **cut-out relay,** *CO.* As soon as the line relay magnet is energized, it attracts its armature and closes the circuit of the **line lamp,** *LL.* This circuit is

completed by the armature and one side of the battery being grounded, as shown at *E*. The operation of removing the receiver at the calling station thus results in lighting the line lamp, *LL*. When the operator sees this, plug *P* is inserted in the jack, *J*, and battery *B* is thrown on the line. The plug has a third strand connected to the sleeve of the plug with connections as shown through a **supervisory lamp,** *SL*, and resistances. When the plug is inserted, current from battery *B* flows around an electromagnet, *SR*, called the **supervisory relay** and the effect is to attract its armature and cut out the lamp *SL*, through the resistance shown. Thus the supervisory lamp is not lit as long as the receiver is off the hook at the calling station.

Another effect of entering the plug *P* in the jack, *J*, is to cause the line lamp to be extinguished. This is accomplished as follows: Current from the ungrounded side of battery *B* flows through the coil of *SR*, which is then energized and attracts its armature which completes the circuit to the sleeve of the plug through the resistances in line and around the lamp. From the ring of the jack current flows around the electromagnet, *CO*, known as the cut-out magnet, to ground. This energizes the electromagnet, *CO*, and its armatures are attracted, breaking the circuit to the line relay. The electromagnet *LR* being no longer magnetized, its armature is drawn away by the action of a spring and consequently the circuit through the line lamp is broken.

When the plug *P* is in the jack and the receiver is off the hook at the calling station, current from the battery *B* is flowing through the two strands of the cord through the plug and jack over the line and through the transmitter of the calling station, thus energizing it and putting it in a condition to vary the intensity of current by the changes in its resistance caused by the sound waves striking the diaphragm.

After the operator inserts the plug in the jack, the **listening key,** *L*, is closed, which throws the central's transmitter and receiver in line with those of the calling station and conversation may be effected. When the desired number is obtained, the plug, *P′*, is inserted in the proper jack, and the **calling key,** *K*, is closed, which connects the generator circuit to the desired station, and at the same time cuts out the cord circuit to *P*, so the calling current cannot

produce any signal at the calling station. When the called station answers, the ringing key is opened which connects P' to the circuit again and the two stations are now connected through the cord circuit and conversation can take place.

When the conversation is over, the receivers are hung on the hooks at each station, with the result that the supervisory lamps SL, one for each station, are lighted, which allows the operator to know that the call is finished. On withdrawing the plug, P, the lamp, SL, on that side is extinguished and in withdrawing P', the one on the right is extinguished. The above operations are accomplished as follows: When the receiver is hung on the hook, the circuit of battery B is broken at that point, and consequently the magnet SR ceases to be magnetized and its armature is drawn away, breaking the shunt circuit around the lamp. Current now flows from the ungrounded pole of the battery through the lamp SL to the sleeve contact on the plug and through the cut-out relay to ground and to the grounded pole of the battery. Finally, on withdrawing the plug from the jack, the circuit on that side is broken and the lamp is extinguished. The same operation holds good for the station on the other end of the cord circuit.

Repeating Coils.—The coils CC and $C'C'$ shown in Fig. 343 are called repeating coils. Though they are shown as four separate windings, they are in reality wound on one core. The object of this winding and of inserting the battery in parallel with the talking stations is as follows: By this arrangement current from the battery divides at the junction of the coils C and C' and part goes to the instruments at each station and for a given difference of potential at the battery a greater current will flow in each portion of the cord circuit than if the battery was connected in series. The circuit in which change of resistance is caused by the transmitter is only that from a station to the switchboard, consequently it bears a greater ratio to the resistance of the line than if the change in resistance took place in the whole line connecting the two stations and the fluctuations of current are correspondingly greater.

A change in the current of either circuit produced by a transmitter acts inductively through the repeating coil of the other circuit and causes corresponding changes of current to act on the receiver of the other line. Thus, when the left-hand station is trans-

mitting, coils C and C act as primary coils and coils C' and C' as secondary coils, and the opposite is the case when the right-hand station is transmitting.

Interior Telephones.

Interior telephone circuits are used where a number of people located close together desire a complete intercommunication with one another. There are several systems that have been devised to meet different requirements and they are generally classified under the following heads:

1. General Intercommunicating System.
2. Common Talking-Circuit System.
3. Central Switchboard System.

In the Intercommunicating System each station can make its own connections without a central operator. This requires that at least one wire for each telephone be connected to every telephone on the system, and besides these, other wires are necessary, depending upon the plan of wiring adopted. It differs from the Common Talking-Circuit System in that as many conversations can take place at the same time as there are pairs of instruments, while the Common Talking Circuit only allows one conversation at a time.

In the Central Switchboard System the services of an operator are necessary and this system does not differ much from regular city exchanges except in the number of the telephones.

Intercommunicating System.—As an example of a successful means of interior communication, a system using the "Ness Intercommunicating Telephone" and manufactured by the Holtzer-Cabot Electric Company is given. This telephone is provided with a switch which automatically returns to the home point when the receiver is hung upon its hook.

This system is usually wired according to one of the following plans:

1. Local talking battery, central ringing battery.
2. Local talking battery, magneto ringing.
3. Central talking and ringing batteries.

Each of these plans has its own advantages, and each requires a different number of connecting wires as shown in the accompanying diagrams.

Fig. 215 shows a system using a local talking battery with a central ringing battery. In addition to a wire for each station two additional wires are required.

If No. 1 station wishes to call No. 4, the switch moving over the circular arc is moved until it rests on terminal marked 4. The button of the switch is then pressed, which rings the bell or buzzer at station 4. As soon as the receivers are off the hooks the local battery is thrown in circuit and talking takes place over the line

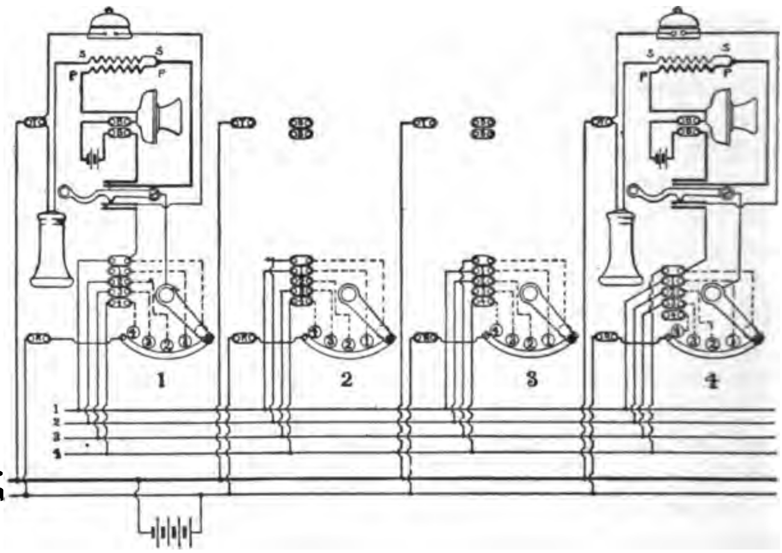


FIG. 215.—Local Talking and Central Ringing Battery.

connecting the two stations and one of the two extra wires. The primary circuit is complete through the heavy lines which include the transmitter. The secondary circuit is completed as follows: Starting from the left-hand terminal of the secondary marked *S*, current flows through No. 1 receiver, to the terminal marked *T* at No. 1, to the connecting wire marked *T*, to terminal *T* at No. 4, through No. 4 receiver, through secondary, to the hook switch at No. 4, then to the blank terminal under the ringing switch, to the blank terminal above the numbered ones, then to No. 4 connecting wire, to terminal No. 4 at No. 1, to ringing terminal No. 4, then

through the switch to the hook switch and from there to the right-hand terminal of the secondary, completing the circuit.

When station No. 1 is communicating with No. 4, No. 2 could be in communication with No. 3. As soon as the calling station has finished the conversation, the receiver is hung upon the hook which returns the calling switch to the home point, and it is now ready to receive a call from any other station.

Fig. 216 shows a system using a local talking battery with magneto call. In addition to the wire for each station, only one additional wire is needed.

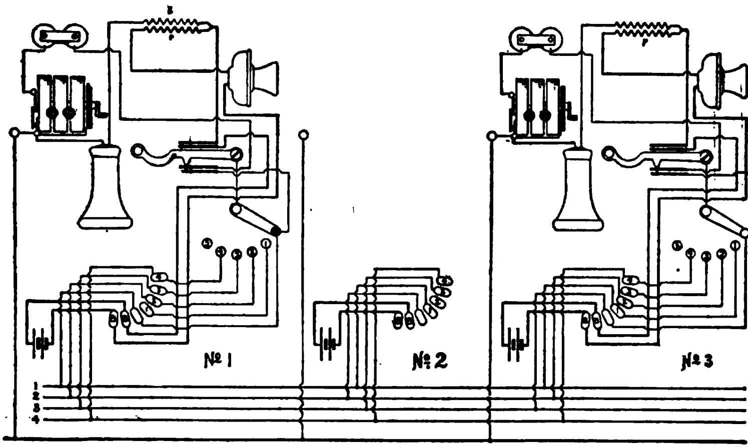


FIG. 216.—Local Talking Battery with Magneto Call.

If No. 1 station wishes to call No. 3 (Fig. 216), the ringing switch is moved to the terminal marked 3 in the curved row of terminals under the switch, and the magneto handle is turned. This throws an alternating current on the line and rings the bell at No. 3. The circuit is as follows: from the left-hand terminal of the magneto to the extra wire between stations, to the corresponding terminal of the magneto at No. 3, past the magneto and through the bell magnets, then to the terminal strip under the hook switch, to the adjoining terminal held together by the switch, to the blank ringing terminal under the ringing switch, to the blank terminal in the other curved row, then to No. 3 wire, back to No. 3 terminal in the curved row, to No. 3 ringing terminal, through the ringing

switch to the hook switch, to the terminal switch under the hook switch, through No. 1 bell and back to the magneto.

As before, when the receivers are clear of the hooks, the talking battery is thrown on the primary circuit containing the transmitters, and the talking currents flow through the wire connecting the two stations and the extra wire.

When the hook is returned to its place at No. 1 station, the switch automatically returns to the home point.

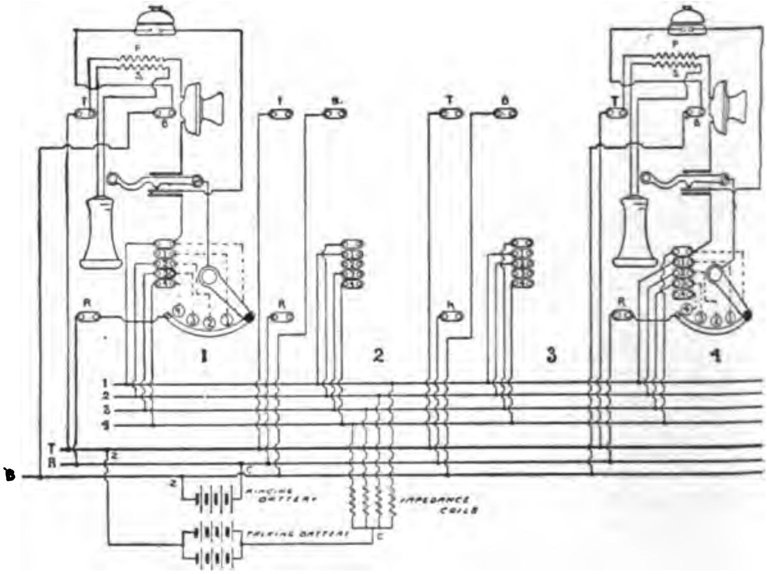


FIG. 217.—Central Talking and Ringing Battery.

Fig. 217 shows a system using both central talking and ringing batteries. In addition to the wire for each station, three extra wires are necessary.

From what has been said regarding the other two systems, this should be readily understood and the ringing and calling circuits followed. It will be noticed that the primary and secondary circuits of the talking circuit are entirely separate from each other, the current from the battery dividing and going through the primary circuit at each station. The currents induced in the secondary only flows through the receivers.

It is usual to make all the wires connecting the stations and such extra wires as may be needed in one cable, each wire being insulated from the other, and the whole completed cable insulated. The wiring from the instruments and connection terminals is made in one cable and lead to connection boxes fitted with properly marked terminals. The connecting cable between stations is then led to these terminal boxes, and connecting pieces are soldered to the wires of the cable and secured to the terminal contacts. An arrangement of desk telephone and terminal box is shown in Fig. 218.

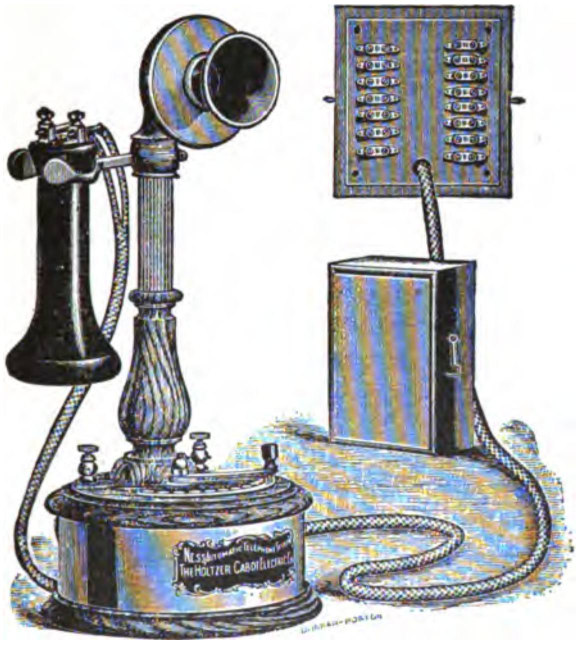


FIG. 218.—Desk Phone with Cable and Connection Box.

Navy Standard Telephones.

Telephone instruments, switchboards and typical circuits as used on board our ships of war are dealt with in Chapter X, Vol. II, Electrical Interior Communications.

CHAPTER XXV.

PRINCIPLES OF WIRELESS TELEGRAPHY.

PART I.

DEFINITIONS.

An **alternating current** is one that periodically reverses its direction in its circuit, flowing first in one direction and then in the other. This alternating current is due to an alternating E. M. F., that gradually increases from zero to a positive maximum then decreases to zero, and then reverses its sign, increases to a negative maximum and then decreases to zero.

The greatest positive or negative values of the alternating current is called the **amplitude** of the alternations.

Each complete set of operations is called a **cycle.**

The time that elapses between the commencement of the current in one direction and its beginning again in the same direction is called a **period.**

The number of periods per second is called the **frequency** of the alternations.

A **high frequency alternating current** is one in which the frequency is reckoned in thousands, and, for convenience, if the frequency is above 1000, such an alternating current is said to be of high frequency and below that number it is said to be of low frequency.

An **electric oscillation** is defined to be an alternating current whose frequency is reckoned in the hundreds of thousands, the amplitude of each alternation being less than the preceding one.

Sustained oscillations are those in which the alternations are very rapid and do not lessen in their amplitude.

Damped oscillations are those consisting of a limited number of alternations, the amplitude of each of which is continually decreasing.

Under damped oscillations, if the lessening of the amplitude is

very rapid, they are called **strongly damped** oscillations, and if it is slow, they are called **feebly damped** oscillations.

Capacity.

All conductors have capacity, depending on their form and size.

The capacity of a conductor is greatly increased when it is placed near a conductor electrified with the opposite kind of charge, so therefore a greater quantity of electricity may be put into it before it is charged to an equal degree of potential.

An arrangement for holding a large quantity of electrification is called a condenser.

The capacity of a condenser depends upon:

1. The size and form of the conductors, usually metal plates or coatings.
2. The distance between the conductors.
3. The capacity of the material (dielectric) separating the conductors.

The dielectric separating the conductors must be of necessity a non-conductor, the usual form being either glass, air, mica, or oiled paper.

The effect of introducing a condenser into a circuit carrying a continuous current is to completely stop the current, as the dielectric is a non-conductor, but on introducing it into an alternating current, the effect is different. The alternating current simply passes into and out of the condenser, changing its sign, as the current charges it first positively and then negatively. The effect is to hold back the current from the E. M. F. impressed in the circuit, and the current is said to *lead* the E. M. F.

The total charge in a condenser depends on its potential and its capacity, and the potential depends on the source of electricity to which it is connected, and by which it is charged.

The practical unit of capacity is the **farad**, and is equal to 10^9 of the absolute unit of capacity, and is the capacity of a condenser that will be charged to a potential of 1 volt by 1 coulomb. The **microfarad** is one-millionth of a farad, or $\frac{1}{1,000,000} \times \frac{1}{1,000,000,000} = 10^{-15}$ absolute units. The capacity of all condensers is stated in microfarads.

Induction.

The phenomenon of induction has been explained in previous chapters, and it has been shown how currents are induced in conductors when they are moving in a magnetic field, or when there is any relative change in the number of lines of force cut by the conductor.

If the magnetic field surrounding a conductor carrying a current is changed due to changes in the current itself, there is induction produced which reacts on the current producing the change in the field. This is not marked in a straight conductor but if it is coiled into a spiral the magnetic field due to each coil reacts on the others and produces greater changes in the flow of current, and the effect is still more marked if the coils are wound on a core of iron.

This phenomenon of **self-induction** acts to oppose changes in the current; that is, if the current is increased, self-induction opposes the increase, and if decreased, it opposes the decrease.

The total amount of cutting of lines of force by a circuit when a current of 1 ampere is turned on or off in it is called the **inductance** of the circuit and is denoted by the letter L, and is numerically equal to

$$L = \frac{S \times N}{C}$$

where S = number of turns in a coil,
N = number of lines of force due to C,
C = current in amperes.

The practical unit of induction is called the **henry** and corresponds to a cutting of 10^9 lines of force when 1 ampere is turned on or off.

As self-induction resists changes in the flow of current, its effects are strongly manifested in currents of constantly changing flow (alternating currents). The resistance of a conductor due alone to changes of current is called its **reactance.**

The combined effect of the resistance (ohmic) and the reactance is called the **impedance.**

The effect of introducing inductance in an alternating circuit is to cause the current to *lag* behind the impressed E. M. F. and thus capacity and inductance produce opposite effects.

PART II.

PRODUCTION OF HIGH FREQUENCY OSCILLATIONS.

A necessary feature of wireless telegraphy requires the production of high frequency electrical oscillations, and this necessity will be shown when the operation of conveying the electrical energy from one point to another is considered.

The electrical discharges necessary to the formation of electric oscillations may be produced by an ordinary Leyden jar, by a condenser, by an induction coil, or by a combination of any of these. The discharge from any of these electrical contrivances may be continuous, intermittent, or oscillatory. The discharge of a Leyden jar or a simple condenser appears to be practically instantaneous, but as a matter of fact, experiment shows that usually it is oscillatory, the period of oscillation being so short that the discharge appears as a single spark. If the discharging circuit could be made without resistance, it is likely a Leyden jar would exhibit a discharge that would oscillate backwards and forwards from one coating to another, the difference in potential between the two coatings becoming less and less, finally arriving at a common zero potential.

The effect of introducing resistance is to choke down the oscillatory discharge, a discharge through a high resistance giving a series of strongly damped oscillations which soon dies away.

Production of Electric Oscillations by the Discharge of a Condenser.—If the two conductors of a condenser are brought to different potentials and they are suddenly connected through a conductor having inductance but small resistance, experiment shows that the equalization of their potentials takes place by means of a discharge consisting of a series of damped electrical oscillations.

There are many mechanical analogues that may be used to show the similarity of damped oscillations, a common one being a simple pendulum. When the pendulum is hanging up and down and motionless there is the force of gravity acting on its bob, but no turning moment, as the arm is zero. As the bob is drawn from the vertical and held at some point, there is now a turning moment tending to return it to its original state of rest. This is the pro-

duct of the force of gravity multiplied by the horizontal distance it has been displaced. The difference between the two forces in the two cases corresponds to the difference of potential in the case of the conductors of the condenser. When the bob is released, it passes through its zero position and swings to the other side, due to the inertia of the mass of the bob. The distance it will be displaced on the opposite side is less than the distance it was on the first, and when again at rest, it swings back, passes through zero and again to the first side with decreased swing. This action goes on .with continually decreasing swing until brought to rest. All the distances on one side correspond to positive potential, those on the other to negative, and they are gradually brought to a neutral or zero potential when the bob is at rest.

The necessary conditions for the creation of mechanical oscillations are that the thing moved must tend to go back to its original position when the restraining force is withdrawn and must have sufficient inertia to overshoot the position of equilibrium in so doing.

In the same way the necessary condition for establishing electrical oscillations in a circuit is that it must connect two bodies having capacity with respect to one another and the circuit must possess inductance and low resistance.

Fundamental Equation of Wireless Telegraphy.—The electrical factors controlling the discharge of a condenser are the ohmic resistance of the circuit, the capacity and inductance in the circuit.

If $R =$ resistance in ohms of the circuit,
$K =$ capacity in farads,
$L =$ induction in henries,

then if $R > \sqrt{\frac{4L}{K}}$ there will be no oscillations in the electrical discharge, but if

$$R < \sqrt{\frac{4L}{K}}$$

there will be oscillations.

In the latter case, if the number of oscillations is n the oscillations will be such that

$$2\pi n = \sqrt{\frac{1}{KL} - \frac{R^2}{4L^2}}.$$

If R is small,

$$n = \frac{1}{2\pi\sqrt{KL}}, \text{ or}$$

the circuit vibrates in its natural period equal to

$$T = 2\pi\sqrt{KL}.$$

Apparatus for the Production of Intermittent Damped Oscillations.—The usual method employed for the production of electric oscillations is the discharge of a condenser of some kind, the charge and discharge being repeated at regular intervals.

The connections of the apparatus are shown in Fig. 219.

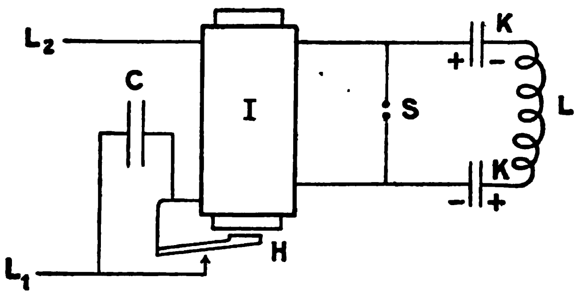


FIG. 219.—Elementary Sending Circuit.

I shows an induction coil, whose primary terminals are connected to the source of supply of electric current marked L_1 and L_2. One plate of each of the condensers K is connected to the terminals of the secondary coil and the other plates are connected in series by the inductance coil L. The terminals of the secondary coil are also connected by the spark gap S.

When current is sent through the primary coil of the induction coil, at each interruption by the hammer H, an E. M. F. is created in the secondary coil. This charges the condensers, the plates connected with the secondary with opposite charges, and those connected with the inductance L of opposite charges, and also opposite to the other plates. The first result of interrupting the primary may be then as represented in the figure by the algebraic signs.

When the spark balls S are a suitable distance apart, the con-

densers being fully charged, the difference of potential between the plates of each breaks down the insulation of the air between the spark balls and the charged condensers discharge themselves through the spark gap, the outer plates neutralizing themselves through the inductance *L*, setting up oscillatory discharges in this coil and it is then said to vibrate electrically.

Electrical Vibration of the Inductance.—It has been shown above that the natural vibration period of the circuit containing the inductance depends upon both the induction and capacity of the inductance coil and is numerically equal to $2\pi\sqrt{KL}$.

Just before the condensers discharge themselves, the total energy is all electric, and at the instant that discharge takes place, the opposite charges move towards each other in the inductance. During this act of neutralization of potential, a magnetic field is set up around the coil, and at the instant of neutralization, all the electric energy has been converted into magnetic energy. The strength of this magnetic field depends on the amount of the moving charges and on the inductance of the conductor.

If there has been but one charging of the condensers, there will be but one discharge, and the magnetic field set up around the inductance having no continuous source of supply, will collapse on the coil, and the magnetic energy will be converted into electric energy, charging again the condensers, but with a less charge than before, due to the energy lost in heating the wires. The phenomenon is then repeated, the energy being first electric, then magnetic, and so on until the charges are fully neutralized.

If there is a continuous source of supply of E. M. F. and the condensers are being continually charged and discharged through the spark gap and the inductance coil the magnetic field induced around the inductance coil cannot collapse on the coil as other fresh fields are continually being set up, and as a consequence the magnetic field radiates off into space, producing the so-called electric waves.

Senders.

The purpose of all senders is to produce high frequency electric oscillations. The general method of producing these oscillations has been illustrated in Fig. 219, but a more general method, illus-

trating practically all the principles of wireless transmitters is shown in Fig. 220, known as the Tesla apparatus.

In this elementary figure are represented all the elements of transmitters for the production of high frequency electric oscillations. The elements are made up as follows:

L_1L_2 = lines for the supply of E. M. F.
I' = primary of the induction coil.
I'' = secondary of the induction coil.
CC = choking coils to extinguish the arc at the spark gap.
S = discharge spark gap.
K = condenser.
L = inductance.
I''' = primary of oscillation transformer (air core).
I^{IV} = secondary of oscillation transfer.
S' = discharge spark gap of oscillation transformer.

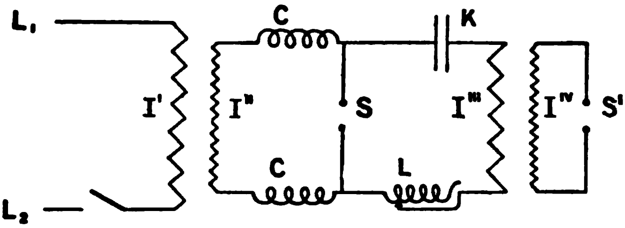


FIG. 220.—Complete Typical Sending Circuit.

Arc Stoppers.—Due to the alternating current produced in the secondary coil of the induction coil, there is a tendency to the production of an arc across the spark gap which would lessen the production of oscillations, and the choking coils *CC* are introduced to prevent this, and with the spark balls a suitable distance apart, the only spark that will pass will be that due to the discharge of the condenser.

Oscillation Transformer.—The primary circuit of this transformer I''' is placed in series with the condenser and spark gap, and this constitutes the circuit in which the electric oscillations are set up by the discharge of the condenser. These oscillations act inductively on the secondary coil, and if this coil has a larger num-

ber of turns than the primary the difference of potential at its terminals will be greater than in the primary by the ratio of the capacities.

When the primary circuit I' is excited, high potential high frequency oscillatory sparks will pass between the spark gap S'.

The other elements of this circuit have been previously described.

Practical Apparatus for the Production of Damped Oscillations.

The elements necessary for the production of intermittent damped oscillations have been shown in Figs. 382 and 383.

Though an induction coil is shown as the means of producing high electromotive force, any other type of generator of high electromotive force might be used. In the majority of practical apparatus, the induction coil, the primary of which is excited by an interrupted continuous current, or alternating current, either direct or produced by some sort of transformer is used.

The construction of an induction coil suitable for wireless use has been described in Chapter VIII.

An ordinary induction coil can be employed as an alternating current transformer by removing its interrupter attachment and supplying the primary direct with the alternating current. For use on shipboard where alternating currents are not available it is usual to make use of a motor-generator, the motor end being wound for continuous current from the constant potential mains and directly connected to an alternating current armature, this arrangement transforming the low potential of continuous current into potential of alternating current. This alternating current is then supplied direct to the primary, and in the form of induction coils generally used, a potential of 20,000 to 30,000 volts can be obtained from the condensers.

If the continuous current is used, the use of some form of interrupter is necessary. These are generally of one of the following classes: **hammer, dipper, motor turbine,** or **jet,** and **electrolytic interrupters.**

Although all these present peculiarities, the one in general use is the turbine or mercury jet interrupter. In this a jet of mercury is

forced out of a small aperture against a metal plate, and the jet is interrupted by means of a toothed wheel, rotated by a motor, which also works a centrifugal pump by which the mercury is squirted. In another form a jet of mercury is thrown on a metal plate and is made intermittent by revolving the plate, the current passing through the mercury. The mercury is covered with oil or alcohol to prevent oxidation. The length of the revolving plates or segments as well as their speed can be varied and so the number of interruptions is well under control.

Electrolytic interrupters present marked peculiarities, in which an electrolytic cell of dilute sulphuric acid as the electrolyte and electrodes of lead and platinum are used. Under certain conditions of E. M. F., current passed through this cell will interrupt the circuit periodically and an enormous number of interruptions can be made.

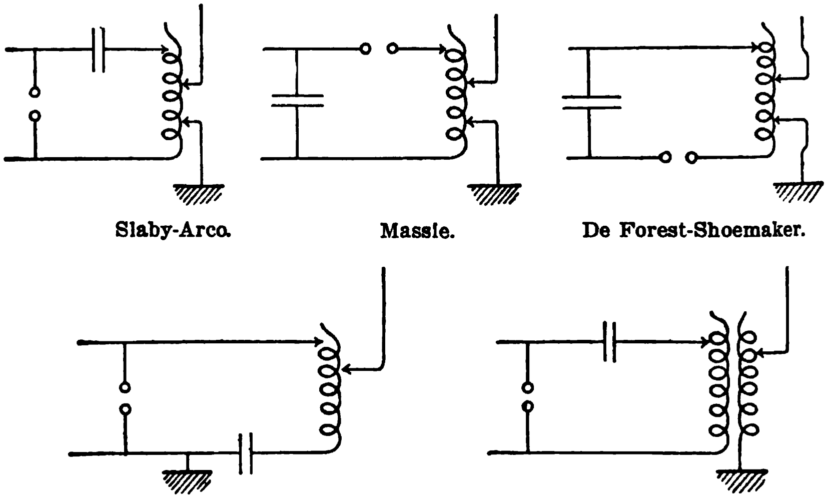
Condensers.—A condenser in its most general form consists of a pair of conducting surfaces separated by a dielectric. Glass, mica, or micanite, and ebonite are about the only solid dielectrics suitable for condenser construction.

A condenser in ordinary use is the Leyden jar, being a glass jar coated inside and outside with tin foil, the tin foil secured to the glass with a thin shellac varnish. These jars are made in various sizes, and as usually made will stand charging to about 20,000 volts. They are arranged to be connected in series or parallel. The inside coating of each jar is connected by some positive form of connection to a terminal leading through the top of the jar and to connect in parallel, all these terminals are connected together and the outside coatings are connected by the jars resting on a common connecting plate.

Plate Form.—Another form of condenser is constructed by covering flat sheets of flint glass with tin foil on both sides, leaving a margin of glass all around with the exception of a small strip on each side which is allowed to project over the edge of the glass, this projection on each side being on opposite corners of the plate. A number of plates are made this way and are then built up, laying them back to back and front to front, so the corresponding terminal strips on each will coincide, and they are secured together, and all the strips of each are connected to common terminal contacts.

Variable Condensers.—Where variable small capacities are required they are made with flat plates with air dielectric, the plates arranged so they can be moved to or from each other.

In another form, a number of fixed pairs of quadrant-shaped plates of brass are placed one above the other in an ebonite box, and all are connected together and to one terminal on the box. In the center is a pivotted vertical rod carrying a number of brass plates which are spaced apart the same distance as the fixed plates. The arrangement is such that every other plate is a fixed one, and



Slaby-Arco. Massie. De Forest-Shoemaker.

Fessender. Stone.

FIG. 221.—Sending Circuits.

every other one a movable one. When the movable plates are turned so as to be directly under the fixed ones, they act as condenser plates, and when turned away they vary the capacity. The dielectric can be air or the plates can be immersed in some form of insulating oil.

There are several other forms of variable condensers used, made on the step-by-step principle or of the sliding type. The former have a definite number of capacities depending on the number of steps, while the latter has any number of capacities between the maximum and minimum values.

Inductances.—Variable inductances for transmitting circuits are almost invariably made on the sliding principle. The variable inductance usually consists of large, bare wire wound in a helix on an insulating frame, with the turns widely separated and fitted with sliders by which more or less turns can be connected to the circuit. Other sliders are provided by which more or less turns can be connected between the aerial and ground.

Sending Circuits.

The following elementary diagrams show the sending circuits of the various forms of wireless sets used on ships of the Navy, and it will be seen that they all conform to the general principles as illustrated in Fig. 221, the differences being in minor changes in the arrangement of the essential parts.

In each case, the lines leading from the left are connections from the secondary coils of the induction coil.

These are all *direct*-connected sets with the exception of the Stone, which is an example of *inductively* connected aerial.

PART III.

ELECTROMAGNETIC WAVES.

The energy of the sending instrument is conveyed to the receiving instrument through the atmosphere, practically, or at least theoretically, through the all-pervading ether that permeates all space and bodies. The present accepted theory regarding the transmission of electricity is that it is due to a series of whirls or streams of bodily movements in the ether, and the energy is conveyed from one point to another by vibrations of the ether particles, in a manner similar to that in which light is propagated. Just as a luminous body sets up vibrations in the ether, so do electrical oscillations when rapid enough cause bodily motion of the substance of the ether, these movements taking the form of waves that travel through space with the same velocity as light. These undulations are partly electrical and partly magnetic, the vibrations causing each being at right angles to each other and both are at right angles to the direction of the propagation of the waves. The movement of

the ether particles is restricted to extremely small ranges of distance, the wave form travelling on as in the case of water waves, where the particles of water simply vibrate up and down.

It has been shown by experiment that these electrical waves have many of the properties of light waves and can be reflected, refracted, and polarized. They also have the property of passing unchanged through brick, stone, or woodwork and through many substances that are opaque to light.

Properties of Electric Waves.

Considering an ordinary wave as produced by simple harmonic motions of the particles of ether, each particle vibrating in its own plane at right angles to the onward direction of the wave and each particle differing in phase by a certain definite ratio from another, the onward form of the wave in a single plane would have the shape of the curve of sines.

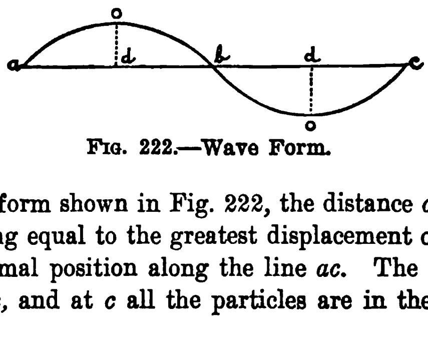


FIG. 222.—Wave Form.

In the wave form shown in Fig. 222, the distance *od* is called the *amplitude,* being equal to the greatest displacement of the particles from their normal position along the line *ac.* The *wave length* is the distance *ac,* and at *c* all the particles are in the same relative phase as at *a.*

The *period* is the interval of time which is taken by the particles in passing through all the relative phases from *a* to *c,* or at the end of one period, all the particles are in the same relative phase as at starting. The period of the wave length determines its *frequency,* the shorter the period, the greater the frequency and vice versa. The number of waves that pass a given point in a certain interval multiplied by the length of one wave gives the total distance travelled by the waves in the given interval, and if that interval be unity, the distance travelled becomes the speed or velocity of the propagation.

The amplitude of the waves depends upon the energy of the electrical discharge producing the waves, just as the amplitude of sound waves caused by a vibrating string depends upon the energy with which the string is plucked. The number of vibrations depends upon the electrical characteristics regulating the discharge, independent of the energy, in the same way that the pitch of sound, or the number of vibrations, produced by a vibrating string is dependent upon its length and independent of the energy setting it in vibration.

If $v =$ velocity of propagation,
$\lambda =$ the wave of length,
$n =$ the number of vibrations,
then $v = n\lambda$.

As the velocity of light waves and electrical waves, according to the accepted theory which has been well verified by experiment, is equal, it follows that the number of electrical waves multiplied by the length of one wave must be equal to the velocity of light.

Experiment shows that the length of electrical waves compared to those of light waves is very long, so the frequency of these waves compared to light waves must be very low. While the frequency of light vibrations is measured in the trillions per second that of the lowest producing the sensation of light being about 392 trillions, those of electrical waves are more often in the thousands. The greatest frequency obtained with electrical waves is about 50 billions per second, which would give a wave length of about 6 millimeters. Frequencies as low as 500 per second have been obtained. The wave length used in wireless telegraphy varies between 100 and 1000 meters, being limited, as later shown, by physical considerations.

The wave length and frequency necessarily depend upon the same characteristics, and a change that will vary one will vary the other. The wave length produced by an organ pipe when blown depends upon the length of the pipe, and similarly it may be said that the wave length of an electrical discharge depends upon the "electrical size" of the apparatus that furnishes the discharge.

The analogy of sound waves in an organ pipe to the electric waves transmitted along a conductor may be carried still further, experi-

ment showing that the nodes and loops of the sound waves find their counterpart in electric waves. Referring again to the form of the wave, the points *a, b,* and *c* represent the nodes or points of no vibration, or rather points at which the resultant of all the vibrations is zero, and 0.0 loops, points representing the position of maximum vibration, or where the particles have the freest motion; and in the electric waves, the points of greatest potential. At the nodes, in the electrical waves, there is the least potential.

An organ pipe closed at one end, when blown, gives as its fundamental note, a sound represented by a wave such that there is a loop at the blown or free end; and a node at the other, the closed end. This is shown in Fig. 223, where the dotted line shows the form of the wave.

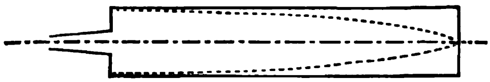


FIG. 223.

In this wave, the amplitude varies from nothing at the closed end to a maximum at the open end, and it depends upon the energy expended in forcing the air into the pipe. The wave length, however, and consequently the frequency depends on the length of the pipe, whether the force of the air be strong or feeble. The amplitude produced by a single strong puff of air, might be obtained by a series of more feeble puffs constantly directed into the tube, if these feeble puffs are rightly timed with each other.

If a conductor with one end insulated while the other end is kept at a constant potential by being connected to earth, is free to vibrate electrically, under the action of an electric force, it is found that there is a node of zero potential at the earthed end and a loop of maximum potential at the free end, while the wave length will depend upon the length and capacity of the conductor. From the nature of the phenomenon producing electric vibrations, it is not possible to obtain a single electric blow sufficient to produce the required amplitude, and recourse must be had to a series of light blows well timed with each other and to the natural frequency of the conductor to produce the desired result, as in the case of the light puffs of air properly timed in the organ pipe.

It is noted that the full wave length as shown in Fig. 223 would be four times the length of the pipe, and so in the case of the electrical oscillating conductor, the length of the conductor is theoretically one-fourth of the wave-length produced.

Aerials.

An aerial wire or **antenna** is a name given to the conductor by which the electrical oscillations are directed into the ether of the atmosphere and is the essential element in all wireless telegraphy.

If in Fig. 220, the balls of the spark gap S' are lengthened out so that the high frequency oscillatory sparks cannot pass between them, the circuit will nevertheless still continue to vibrate electrically, setting up magnetic fields around it when the induced current is alternating back and forth due to the inductive influence of the primary coil I''', and throwing off into space the electromagnetic waves, if the source of power is being put at intervals into the primary coils I'.

If the lower ball of the spark gap S' is bent around and connected to earth, and the upper ball bent around and lengthened vertically, we shall have the aerial as universally used for wireless telegraphy, the aerial still vibrating electrically, with the lower end earthed and the upper end free.

The action of the electrical vibration, or the induced alternating current, in the earthed aerial may be best illustrated by considering the spark gap S as being directly in the aerial.

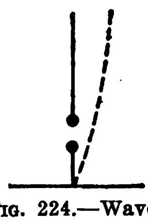


FIG. 224.—Wave on Earthed Aerial.

Fig. 224 shows such a case. If now the two sides of the spark gap are connected to the opposite plates of a condenser, the upper part is charged to a high potential and the lower part to zero potential, that of the earth, and discharge takes place across the gap. Just before discharge takes place the upper portion of the aerial has a certain capacity with regard to the earth and takes a certain charge, and as the spark has a low resistance, the discharge is oscillatory, but much damped, as the energy is rapidly radiated.

The earthed end of the aerial is at zero potential, or there is

a node of potential at that point. It then follows that there must be a loop of potential at the upper or free end, and the fundamental oscillation excited in the whole length of the wire is one in which the potential increases all the way up the wire from the earthed to the free end, and this wave form is shown by the dotted line in Fig. 224.

The distribution of the current is such that there is a maximum current at a potential node and minimum of current at a potential loop.

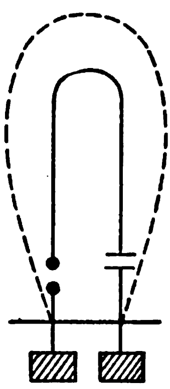


FIG. 225.
Looped Aerial.

The elementary form of the wave would indicate that the aerial should be one-fourth of the wave length of the oscillation. Owing, however, to the inductance in the aerial, experiment shows that the length is more nearly equal to one-fifth of the fundamental wave length.

It is not necessary that the aerial should be directly connected to the circuit containing the spark gap, but it can be connected inductively, as shown in Fig. 220 in the elementary transmitter, formed as stated, by bending the arms of the spark gap S' around, earthing one, and lengthening the other vertically.

Looped Aerials.—A looped aerial is one made in the form of a loop with its two ends connected to earth, one end through the spark gap and the other through a condenser, as illustrated in Fig. 225.

These are used in some forms of wireless sets, and present the peculiar circumstance that they will radiate for some frequencies of oscillation and not for others. If the lower condenser plate is not connected to earth, there is no radiation from the loop as a whole. Some characteristic forms of aerials are shown in Fig. 226.

Coupling.

Direct and Inductive Coupling.—Direct coupling consists in connecting the aerial directly to some point on the oscillating circuit, usually the inductance, another point on the inductance being connected to earth.

Inductive coupling consists in coupling the oscillating circuit to the aerial inductively, the secondary of the oscillating transformer being in series with the aerial.

These are illustrated in Figs. 227-228.

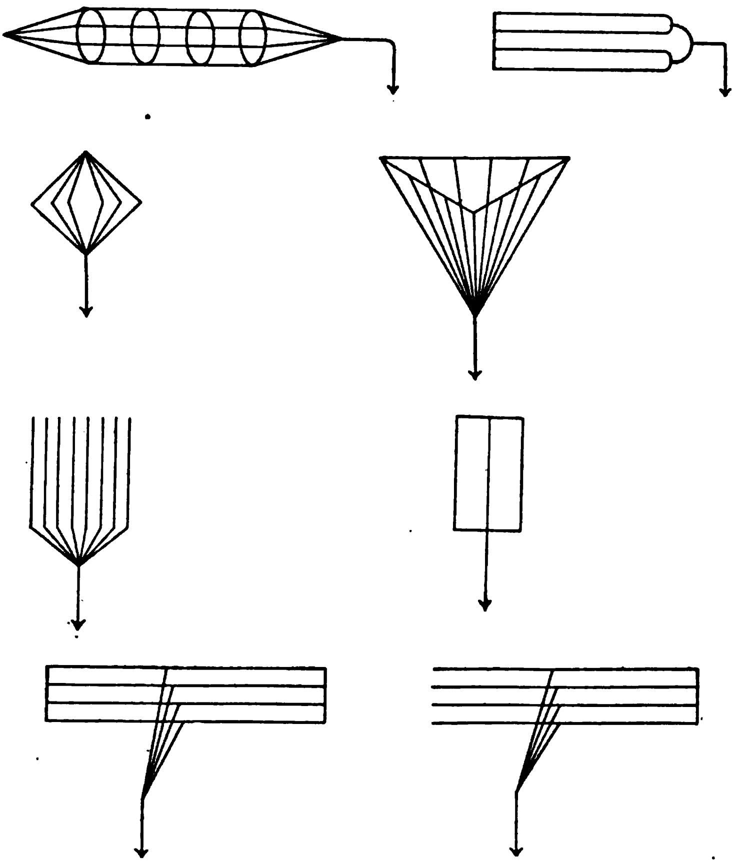


FIG. 226.—Typical Forms of Aerials.

Open and Closed Circuits.—The closed circuit is that part containing the spark gap, condensers and inductance, and the open circuit is that part containing the aerial with its portion of the inductance.

In direct coupling, the open and closed circuits have some turns of inductance in common, as the turns of the inductance embraced between the connections 1 and 2 in Fig. 227. When the common turns of the closed and open circuits in directed connected coupling are large in number, or the coils of the inductively connected circuits are close together, the circuits are said to have a **close or tight coupling.** In this case the energy is radiated very fast from the aerial and the oscillations are correspondingly damped. When the common turns of the closed and open circuits are few in number, or the inductively connected coils are few, the circuits are said to have a **loose coupling.** In this case, the oscillations are kept up more strongly and the radiation from the aerial is less.

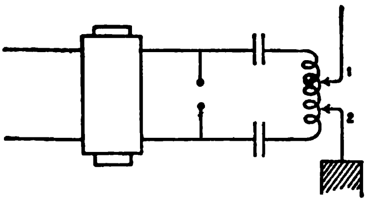


FIG. 227.—Direct Coupling.

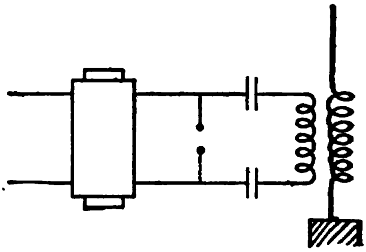


FIG. 228.—Inductive Coupling.

Each of the closed and open circuits has a natural period of vibration, due to its capacity and inductance, and when they are adjusted to have the same period of vibration, they are said to be in **tune** with one another.

Though each of the closed and open circuits may be tuned with each other before coupling, yet when they are coupled, the resulting period is not the same as either, and experiment shows that the resulting oscillation has two periods of vibration, and consequently two different wave lengths.

In close coupling, there results two periods of vibration, one longer and one shorter than the natural period of either circuit.

In loose coupling, the resulting two periods more nearly coincide with the natural period of each circuit.

The **percentage of coupling** is the ratio of the difference of the

periods of the two waves sent out to the natural period of each circuit; or what amounts to the same thing, the ratio of the difference in length of the two waves sent out to the natural wave length.

Detachment of Electromagnetic Waves.

Let Fig. 229 represent the aerial connected inductively to a closed oscillating circuit.

Just before discharge at the spark gap takes place, all the energy is stored in the condenser plates and is electrostatic. At the instant of discharge, the charges move towards one another as indi-

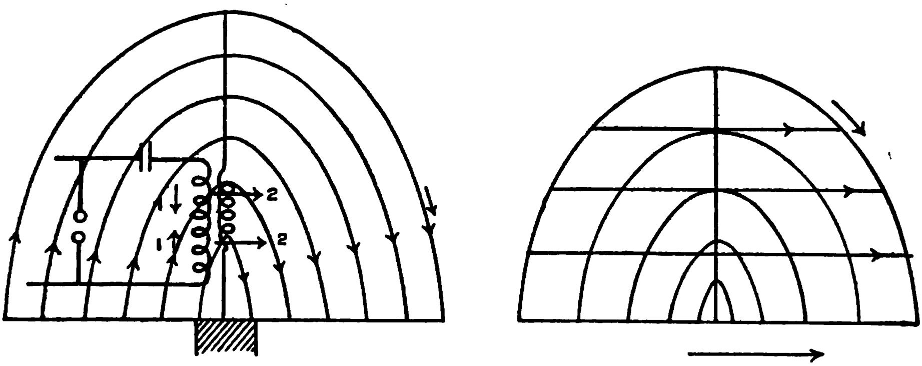


FIG. 229.—Detachment of Waves.

cated by the arrows, 1—1, and induce **magnetic** lines of force in the inductance of the aerial, whose direction is perpendicular to the direction of the aerial, as indicated by arrows 2—2. Due to the induction of these magnetic lines of force a current is induced in the aerial. These induced currents vary in intensity along the aerial and have the greatest value at the earthed end, as at this point it has been shown that the potential is least or the rate of change of current greatest, and have the least value at the top end of the aerial. This moving current or charge carries with it its **electric** lines of strain. There is a lateral pressure in the ether tending to keep these lines apart from one another and a tension along them tending to shorten them.

The result of one single discharge at the spark gap might then be graphically represented by the curved lines of electric force or electrostatic lines of strain as shown in the figure radiating off each side of the aerial. It must be remembered that this condition of electric stress is produced in all directions around the aerial, making a semispherical surface bounded by the furthest removed electrostatic line of force. Although this surface is represented as a spherical ring, it may not be so, the only condition being that it is a closed surface. The electrostatic lines are closed through the ground, being the result of the common potential.

The result shown is that at the instant after discharge. The reaction immediately follows; the lines of force, both electrostatic and magnetic collapse on the aerial, and if there are no more oscillations, the lines of force are dissipated, the electrostatic lines closing on themselves through the ground and being completely neutralized.

However, as the closed circuit is vibrating rapidly, the outward rushing of the second series of lines takes place before the first can entirely collapse and so pushes them, as it were, further along, and as they are not entirely collapsed the energy of the succeeding oscillation causes the electrostatic lines to be pushed further away. The magnetic lines are increasing at the same time. All matter possesses inertia and the collapsing lines of force cannot immediately return owing to the inertia of the imponderable ether.

Each succeeding oscillation along the aerial finds the electrostatic surface pushed further and further along until finally it is detached from the aerial and travels onward through space as a wave form with its two characteristic vibrations at right angles to each other. The wave is shown as a semispherical ring travelling along over the ground and directed by it. The lines of vibration of the ether particles producing electrostatic induction form meridians of this sphere or vertical circles and those producing electromagnetic induction are at right angles, and form circles of latitude, or horizontal concentric circles in a section of the ring.

These waves are propagated in all directions and the direction of propagation is at right angles to the directions of the two vibrations.

These waves maintain continuous contact with earth and are not

propagated throughout space and cannot be reflected by the earth into space as might be the case if they were completed on themselves independent of the earth. This earth connection also facilitates the transmission of the wave in a direction parallel to the earth's surface. The earth guides the waves, allowing them to follow its curvature and pass obstacles if they are not too large in proportion to the size of the wave. The dimensions of the wave increases with the height of the aerial and a big wave will more easily overcome a distant obstacle than a small one. The dimensions do not refer to the length or amplitude of the wave which depends respectively on the frequency of the oscillation of the aerial and on the energy of the sending apparatus, but to the volume, or it might be said, the mass of the waves. The longer the waves, the more easily they will flow around obstacles, so that on the other side the vibrations are still perceptible, and long wave length is a very desirable quality of these electromagnetic waves for successful wireless work.

PART IV.

RECEIVING CIRCUITS.

It has been shown that the wave surface detached from the aerial of a sending station proceeds through space as a continually increasing disturbed mass of ether in which there are two distinct lines of vibrations of the ether particles at right angles to each other. One set of lines of vibrations (magnetic) are practically parallel to and the other (electrostatic) are perpendicular to the earth's surface.

If an earthed conducting wire is held vertical to the earth's surface in a region where these waves are travelling the lines of force will direct themselves towards it in order to go to earth through it, and the higher the aerial the more lines of force it will be able to embrace. This conductor will be cut at right angles by the magnetic lines of force, which are proceeding as a series of horizontal concentric circles, and will induce alternating potentials in it. Similarly, a horizontal conductor will be cut by the electrostatic lines of force and alternating potentials would be induced in it. A conductor in any position between the vertical and horizontal

positions will be acted upon by the combined action of both series of lines of force.

If this receiving aerial has a natural period of vibration due to its capacity and inductance equal to that of the passing waves, the amplitude of induced currents will gradually rise, due to the successive impacts of each advancing vibration, the effect of each one being added to the preceding one.

The analogy of this is seen in the ringing of a heavy bell. On first drawing the bell rope, the bell may barely move, but a second pull rightly timed will cause an increased vibration and soon it may begin to swing in its own particular period of vibration, and each pull of the rope at the proper time will increase its swing until finally the bell rings. The bell then has been rung by a series of very light pulls, each correctly timed to correspond to the natural vibration period of the bell as it is suspended.

If the periods of the wave and the aerial are the same, each passing wave will add its potential to that due to the preceding one and the amplitude of the vibration will soon reach its maximum, when the aerial will radiate as much energy as it absorbs.

To increase the natural frequency of its vibrations, the aerial is either connected direct or inductively to a closed circuit in which there is both capacity and inductance and in which either may be varied.

The receiving circuit then is similar to the sending circuit, the place of the spark gap being taken by the detector, by which the vibrations of the closed circuit are made manifest.

Whatever form of detector is used, it must be sensitive enough to respond to the maximum amplitude, or greatest potential, of the oscillating circuit.

The following elementary diagrams show the receiving circuits of various forms of wireless sets, and it is noticed they contain nothing but the aerial, inductance, and capacity in circuit with the detector, which in each case is marked *D*.

Some of these present peculiarities, notably the Stone, De Forest, and Shoemaker circuits. The circuit of the Stone system is inductively connected, and the middle circuit, as shown, is called a **weeding out** circuit. This is used to prevent interference when

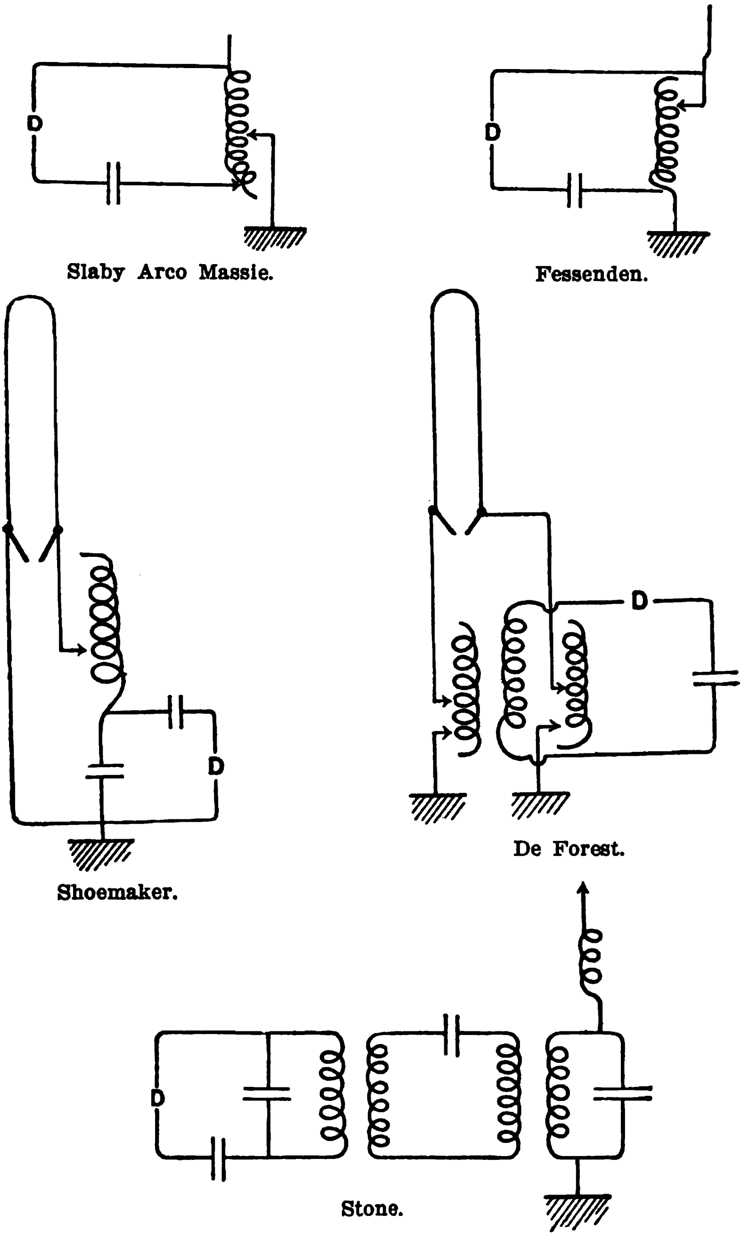


FIG. 230.—Receiving Circuits.

very close tuning is sought, but can be cut out wnen it is not necessary.

The De Forest and Shoemaker use the loop aerial, the controlling idea being the setting up of **stationary waves** in the closed circuit, which is grounded. By changing the relative positions of the capacity and inductances, the nodes and lopes of the stationary wave may be varied so as to produce maximum current or maximum potential at the detector, depending on the form used.

Detectors.

Each portion of a receiving circuit in a space through which electromagnetic waves are passing is subjected to an alternating electric force followed by a magnetic force at right angles to it, and all wave detectors are devices for detecting the existence of these forces.

The most general forms of detectors may be classified under the following heads: **Contact, thermal, magnetic,** and **electrolytic** detectors.

Contact Detectors.—The most usual form of contact detector is known as a **coherer,** and there are many patented varieties of this device. In its elementary form, it consists of an exhausted glass tube, provided with little pistons, which act as terminals for connection to the receiving circuit, and between which is some form of powdered metal. The conduction of powdered metal acts in a peculiar manner. A loose heap scarcely conducts electric currents at all, owing generally to the want of adhesion of the particles and to the resistance of air films between the particles. If an electric oscillation occurs near such a coherer, the powder becomes a good conductor and the particles cohere, as the resisting films of air are broken down by the successive internal discharges from one particle of the powder to another, and it will remain a good conductor until the continuity of the particles is destroyed by shaking or striking them.

The electromagnetic waves striking the circuit of which the coherer forms a part, induces an oscillating current through the coherer powder which causes a succession of very minute sparks from one particle to another and which produces electrical con-

tinuity throughout the powder. The coherer is inserted in a local circuit with a few cells in series with a relay, and when current flows from the local battery through the coherer and relay, the attraction of the relay armature closes another circuit which contains the recording instrument.

The coherer is used in the Slaby Arco system and is illustrated in Fig. 231.

Detectors of the coherer type are now rarely used in ship installation, having given way to other forms and principally to some form of electrolytic detector.

Carborundum Detector.—This wave responsive or wave detecting device comprises a body of crystalline silicid of carbon, known generally as carborundum. The body of crystals forming the mass is composed of carbon and silicon in a chemical combination, forming what is known chemically as carbid of silicon, or silicid, or more

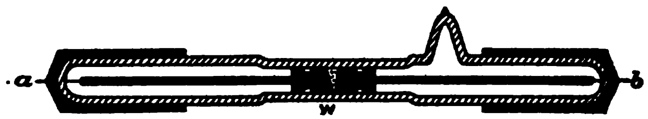


FIG. 231.—Slaby Arco Coherer.

generally as carborundum. It is a highly refractory material, extremely hard and is relatively a poor conductor of electricity.

This substance may be connected in the receiving circuit in many different ways, all of which act efficiently as wave detectors. It should be interposed between the connecting wire from the aerial and the connecting wire to ground. It may be simply interposed with the two connecting wires secured to it in any suitable way, either by direct contact, or through contact pieces holding the carborundum; or it may be held between the points of adjusting screws which are connected respectively to the aerial and ground. Again the carborundum may consist of two pieces, each in connection with the connecting wires and resting lightly against each other on relatively sharp edges.

One of the connecting wires may be connected to a piece of carborundum, a sharp point of which may rest in an electrolyte, such as mercury, or an acid, or an alkaline fluid, while the con-

necting wire to the ground is secured to the vessel containing the electrolyte, if it is a conductor; or it may be immersed in the electrolyte or even connected to another piece of carborundum which rests in the fluid.

In all cases, the usual telephone receiver is connected around the detector with a battery included in the circuit; although if the two ends of the detector are connected to the ends of a looped aerial, one side of which is grounded, the battery may be dispensed with, if the telephone receiver is connected to the same points on the aerial.

Crystalline Detectors.—The carborundum detector is one form of many crystalline detectors whose action in cohering or decohering is not thoroughly understood. One other form that seems to depend upon the resistance of imperfect contacts consists of two crystalline minerals, *zincite* and *copper pyrites.* If a piece of copper pyrites is secured to the connecting wire from the aerial and a piece of zincite to the ground connection, there can be found one degree of contact between them which acts as a very perfect detector; the usual telephone receiver and battery being connected around the contact of the two crystals.

Thermal Detectors.—One form of detector based on thermal action is used in the Fessenden system, although the system as applied to ships of the navy uses a form of electrolytic detector.

The principle of this thermal detector depends upon the property of metals presenting a higher electrical resistance as their temperature increases. It consists of a silver wire bent into the shape of a V having a diameter of .05 mm. with a core of platinum .0015 mm. in diameter. The lower end of this V is immersed in nitric acid, which dissolves the silver for a short length of the platinum. The wire is contained in an outer covering of silver, which is held in a glass vessel from which the air has been exhausted, and through which connecting wires lead from the outside and are soldered to the silver wire.

When the exposed platinum wire at the point of the V is in circuit with the electric waves, it heats rapidly, and as rapidly cools when the wave ceases. In the same circuit is placed a battery and a telephone, the variation of the resistance producing variations in the telephone current which produces sounds more or less pro-

longed, according to the train waves, and these are longer or shorter as the wave trains sent out by the sending circuit or of greater or shorter duration.

Magnetic Detectors.—This form of detector is based on the principle that rapidly alternating currents permanently modify the magnetization of a magnetized steel bar. The electric waves striking such a magnetized bar induces currents in a conductor wound around it which may be made manifest in several ways. After a change in the magnetization due to the impact of the oscillating current, it must be remagnetized before it is in a position to again be affected. The general principle is exhibited in Fig. 232.

The magnetized substance is a bundle of very fine steel wires, insulated one from another. Around this is wound the aerial, with the other end connected to earth. Over this is a coil of a

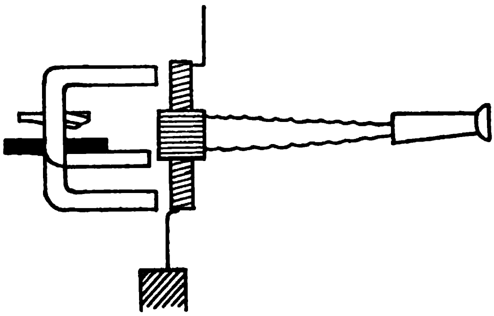


FIG. 232.—Magnetic Detector.

great many turns of fine wire to which a telephone receiver is connected. Due to the demagnetization of the bundle of wires currents are induced in the coil which traverse the telephone and owing to their alternating character produce sounds, of a duration depending on the length of wave train.

The magnetism is restored by a revolving horseshoe magnet which constantly remagnetizes the bundle of wires.

This form of detector was devised by Marconi but has not been used in ships of the Navy. Its practical working form is different but the principle remains the same.

Electrolytic Detectors.—This form of detector depends upon the power of electric oscillations to affect the polarization of small metallic surfaces immersed in an electrolyte. The general principle in most detectors of this type is explained in a description of the Schlœmilch Detector. This is illustrated in Fig. 233.

A primary cell is arranged to consist of two electrodes, one of platinum, *A*, and the other lead, *B*, and the electrolyte of dilute acid. The platinum anode *A* is made very fine, both in its length and diameter, being about .01 mm. long and .001 mm. in diameter, and arranged so that the point just touches the surface of the electrolyte.

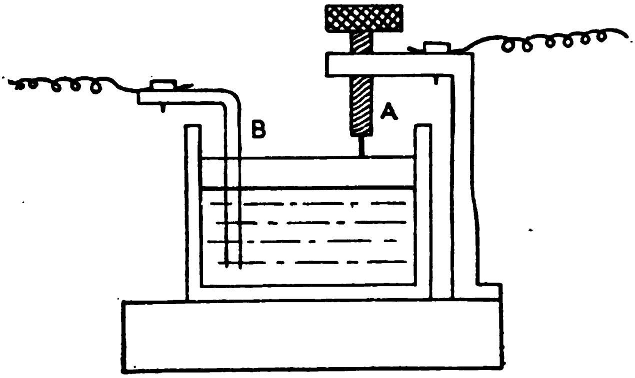


FIG. 233.—Schlœmilch Detector.

This electrolytic cell is placed in series with another primary battery with a slightly higher E. M. F. and included in the same circuit is a resistance coil and telephone receiver. This primary battery sends a small current through the electrolytic cell and soon *polarizes* the electrodes; that is oxygen gas is liberated from the acid by the current and the bubbles collect on the small platinum anode. The resistance of the gas so increases the total resistance that the current from the primary battery soon falls to zero, or practically so.

If now the electrolytic cell is connected to a circuit in which electric oscillations are set up, these oscillations momentarily depolarize the surface of the platinum anode, which suddenly reduces

the resistance of the cell. Current then as suddenly flows from the primary battery, and through the telephone in which a sound is heard, its duration depending upon the impact of long or short trains of waves. These sounds are then of shorter or longer duration, corresponding to the dots and dashes of the telegraphic code, the length of train wave made by the length of time the sending key is kept in contact.

The electrolytic cell as practically used varies in details, some using platinum cells as in the Fessenden type, others glass cells as in the De Forest type. It is usual to seal the fine wire of the anode in a glass tube, leaving just the minutest portion of the surface exposed. In this form the tube may be immersed in the electrolyte, and the care necessary to keep the fine point adjusted to the surface of the liquid is eliminated.

In order that the potential of the primary battery may be adjusted to the proper value for just polarizing the anode in the electrolytic cell, its terminals are connected through a potentiometer or variable resistance whereby the current can be accurately controlled. All forms of wireless sets used on ships of the Navy are so connected with the exception of the Shoemaker type.

The Shoemaker type of electrolytic cell does not require an extra primary battery, but uses its own current to depolarize itself. It consists of a fine platinum wire sealed in glass as the positive electrode and amalgamated zinc as the negative electrode, both dipping into an electrolyte of 20 per cent solution of sulphuric acid. The telephone receiver is simply shunted across the terminals of the detector.

Detector Circuits.

Referring to Fig. 230, in which elementary diagrams of various forms of receiving circuits are shown, the detector in each case is marked *D*. The detector circuits shown in Fig. 234 may be considered the complete diagram of the detector circuits.

Inductance and Capacity of Receiving Circuits.

The object of inductance and capacity in the receiving circuit is to give it a certain period of vibration in order that it may respond

to a certain frequency or wave length of the sending circuit. As the natural frequency depends upon both of these factors, and for the purposes of changing the wave length, it is usual to fit the receiving circuits with both variable inductances and capacities.

Variable Inductances.—Variable inductances are usually of the step-by-step or roller form. A convenient form of step-by-step inductance is made by making a cylindrical coil of insulated wire

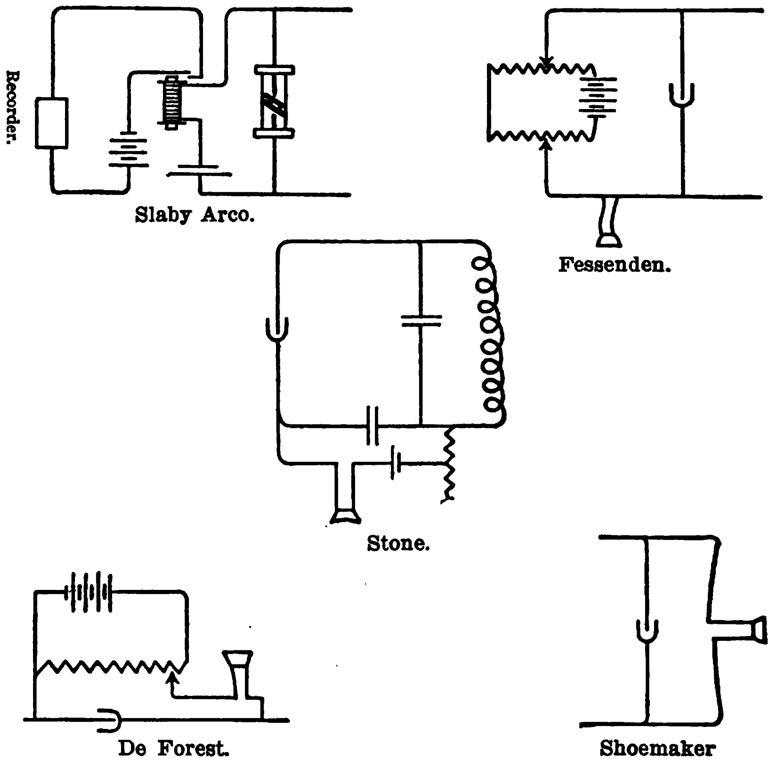


FIG. 234.—Detector Circuits.

wound on glass, or some form of hard rubber with one point on each turn bare. A sliding contact moves across these points, giving as many adjustments as there are turns in the coil.

Step-by-step inductances are also sometimes made with plug steps, giving a limited number of changes.

Roller type of inductances may be of the single-roller or double-roller type. In the single-roller type a bare wire is wound on a groove cut in an insulating cylinder, and against this wire is pressed a sliding contact. By revolving the cylinder any fraction of its length can be put in circuit. In the double-roller type a bare conductor runs from one insulating cylinder to another. On one cylinder the turns of the wire are insulated and on the other they are in contact, so any desired length can be added to the circuit.

Variable Capacities.—These are generally of the step-by-step or sliding type previously described.

Variable capacities in receiving circuits are more essential than variable inductances, as a strong pronounced natural period can only be obtained by a large inductance, leaving the variation in wave length to be accomplished by the variable capacities. If the wave length is to be very greatly increased it can be done by adding a large inductance to the aerial at some point that will not interfere with the inductance necessary for the absorption of power in the closed circuit.

PART V.

WAVE METERS.

In any circuit containing resistance, capacity, and inductance, if the resistance is small in comparison with the inductance, the number of oscillatory vibrations per second such a circuit will follow will be given by the formula:

$$n = \frac{1}{2\pi\sqrt{KL}},$$

where $K =$ capacity in farads,
$L =$ inductance in henries,
and $n =$ number of oscillations per second.

Therefore, knowing K and L for any circuit, which values can be found by independent measurement, n may be calculated, from which the wave length may be found from the formula:

$$V = n\lambda \quad \text{or} \quad \lambda = \frac{V}{n},$$

where $\lambda =$ the wave length, in the same units as V, which is the velocity of the electromagnetic waves or the velocity of light.

Thus the length of wave corresponding to the natural vibration period of any circuit containing inductance and capacity may be found. Wave meters are circuits containing these factors, with provision for varying their values and for each combination of which the wave length has been calculated.

Donitz's Wave Meter.—An inspection of this device (Fig. 235) will show a closed circuit containing inductance and capacity in series. The inductance is in the form of a ring with plug terminals by which it is connected to the condenser. This last occupies the main space devoted to this meter and consists of several semicircular metallic sheets, parallel to one another and fixed; while an equal number of similar semicircular sheets are movable around a vertical axis, and so arranged that they can be fixed to slide more or less into the spaces between the fixed sheets, thus constituting a condenser of variable quantity. These plates are contained within a circular vessel which is filled with oil.

The knob that moves the plates is provided with a pointer which moves over a scale indicating the wave length for the given inductance and the capacity of the condenser corresponding to the position of the plates at that time. The instrument is provided with three separate inductance coils of values 2.8, 12.1, and 50 microhenries, and there are three scales provided, one to be used for each of these coils.

The indicating apparatus shown on the left consists of a very small spiral of platinum sealed in an air thermometer, and connected inductively to the main circuit.

When the circuit is vibrating in its natural frequency, the greatest current is induced in the platinum spiral which is heated and the air thermometer then registers its maximum value.

Slaby's Helix Wave Meter.—This form of wave meter depends upon the principle that if a helix of uninsulated wire is held in the hand and the other end held near a circuit in which electric oscillations are taking place, the length of the helix can be altered until the stationary oscillations excited in it are of the same frequency as those in the circuit under test. The wave length will then be four times the length of the helix.

The practical instrument is made of an insulated copper wire

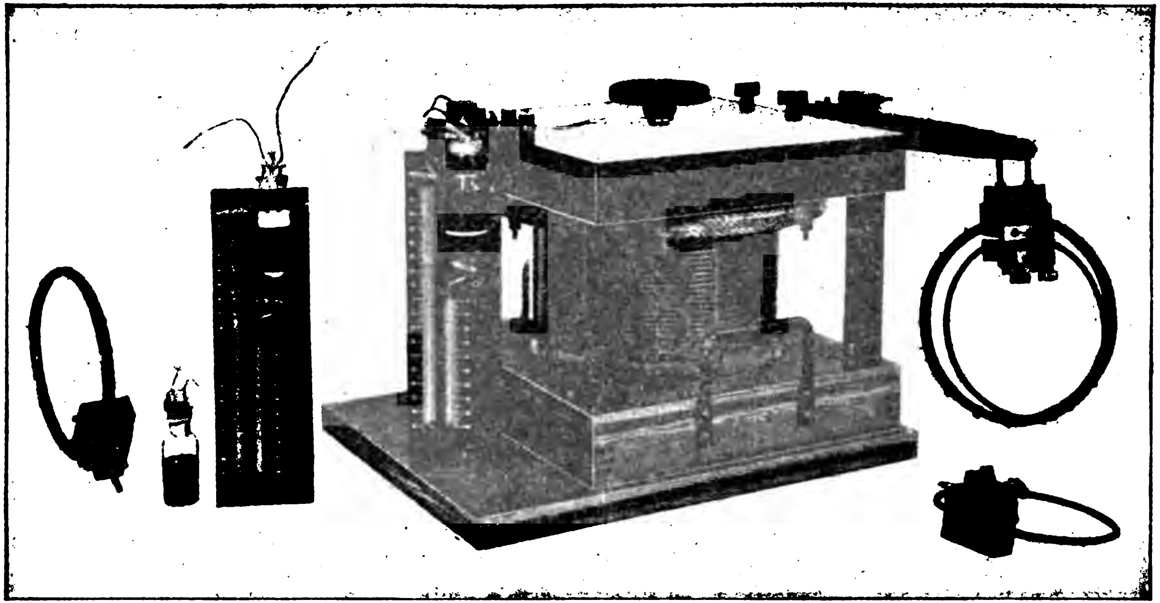


FIG. 235.—Donitz's Wave Meter.

wound in a close spiral on a glass tube ¾ inch in diameter. The lower end of the copper wire is in connection with a metal handle attached to the glass tube while the upper end is in connection with a fluorescent sheet. This is formed of a small sheet of paper covered with crystals of barium platino cyanide with gold-leaf in a fine state of division rubbed on the surface. This prepared paper is then inserted in the upper end of the tube and held by a stopper.

A metal rod is provided which is connected to an earthed wire. When the end of the tube containing the fluorescent paper is held near the circuit in which the oscillations are taking place and the earthed rod is moved along the spiral, there will be a point in which the glow in the prepared paper is greatest. At that point the wave length is read on the scale opposite the metal rod.

Fleming's Wave Meter.—This form of wave meter also depends upon the establishment of **stationary waves** upon a helix brought near an oscillating circuit. Its general construction is illustrated in Fig. 236.

The inductance consists of an ebonite tube with a helical groove cut on it, in which is wound bare copper wire whose ends are secured to collars on the ebonite tube. Parallel to this helix is fixed a sliding tubular condenser. This consists of inner and outer tubes of brass with a tube of ebonite between them. The outer tube has a collar *k* at one end to which is attached an ebonite handle *h*. A movement of this handle moves also a collar *K* on the inductance and carries a pointer which moves over a scale *SS*. One end of the inductance helix is connected to the inner tube of the condenser through the bar $L_1L_2L_3$. A vacuum tube *V*, preferably one filled with rarefied neon is connected with one end of the inner condenser tube and the other end should be connected to earth, when measuring wave lengths.

To measure the wave sent out by an aerial, the handle *h* is moved until the vacuum tube glows most brightly and the scale reading will be the wave length.

The form of wave cannot be plotted by this meter as there are no means of determining the relative brightness of the glow, but it will only show the length of the two waves radiated by the aerial.

In addition to being used as a wave meter, this instrument can

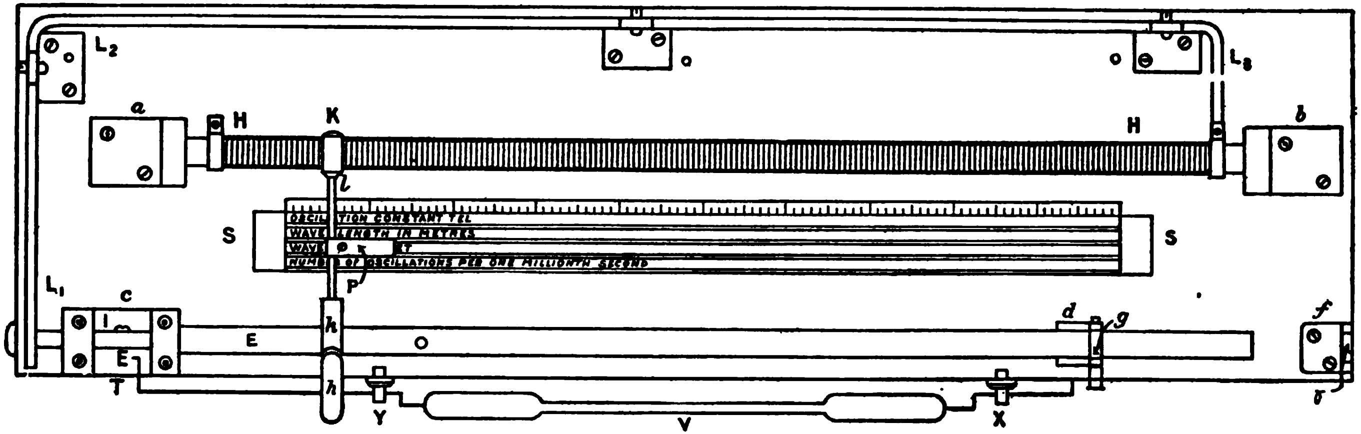


FIG. 236.—Fleming Wave Meter or Cymometer.

also be used to measure small inductances and capacities, one reading of the scale showing the oscillation constant, $\sqrt{KL}$, expressed in centimetres.

Hot Wire Ammeter.—This instrument is for use in the open circuit and measures directly the current in the aerial, and to be accurate the whole current should pass through the working wire of the instrument. As its name implies it measures the heat generated in the aerial, and the heat generated acts to expand a conductor which moves a pointer over a scale indicating the number of amperes flowing. If the pointer moves off the scale, its terminals are shunted by suitable resistances whose values are known.

When the closed and open circuits have the same frequency a maximum reading will be obtained on the ammeter, but it will not in any way indicate the wave length or degree of coupling of the two circuits, though it will show the difference of energy radiated dependent upon the tightness or looseness of the coupling.

Pierce Wave Meter.—The Pierce Wave Meter is very similar in design to the Donitz Meter. The place of the air thermometer is taken by a telephone receiver and it is fitted for measuring both long and short waves, and when used with the former, there is included in the circuit an extra inductance coil of fine wire. When the frequency of the meter and oscillating circuit are in tune, the humming noise produced in the telephone receiver is a maximum, and a slight change from complete resonance will destroy the sound.

The wave meter can be used as a sender by disconnecting the telephone receiver and substituting in its place a small spark gap, which can be actuated by a small spark coil.

PART VI.

TUNING.

By tuning or syntonizing is meant the operation of connecting the different circuits of a wireless outfit so that they shall all vibrate in the same period, or adjusting the closed and open circuits of the sending and receiving circuits to the same wave length.

There are two conditions necessary to insure the tuning of two

stations with one another; the sending apparatus should radiate waves of well-defined period and but slightly damped, if at all, and the frequency of vibration of the different circuits should be capable of easy adjustment.

Between two stations tuned for the same wave length it is possible to signal with sending apparatus of much less power and to receive with apparatus of less sensibility than if they were not so tuned.

The different circuits are tuned by means of any of the standard wave meters previously described, the operation consisting in setting the pointer opposite the desired wave length and then bringing the circuit under test in syntony with it by changing its variable factors. Most sending circuits have fixed capacity and variable inductance, while in receiving circuits, the opposite is the case. If variable inductance is needed in a receiving circuit, it can be placed where it will not affect the mutual induction of the closed and open circuits.

The question of wave length is one dependent on the possible length of aerial with due consideration of sufficient inductance for proper coupling. The greater the wave length the more power can be used, and it has been shown that long wave length is of advantage in passing around obstacles when sending over land. Four hundred and twenty-five meters has been adopted as the standard wave length for ships of the Navy.

The sending circuits are usually tuned first and the closed and open circuits are tuned separately.

To Tune the Closed Sending Circuit.

By Donitz's Wave Meter.—Disconnect the closed circuit from the open circuit, if it is directly connected. Set the pointer that moves the variable capacity of the meter to the desired wave length, and connect one of the inductance coils to its terminals. Bring the inductance coil of the meter parallel to the plane of the inductance of the closed circuit and close to it, a foot or so, and arrange so that the circuit produces a clear, bright spark of moderate length. This will induce oscillating currents in the meter circuit and produce heat in the thermometer coil and the thermometer will indi-

cate a certain reading. Now vary the inductance of the closed circuit until the thermometer gives its maximum reading. The two circuits will then be vibrating in tune, and the wave length of the closed circuit will be the same as that of the meter. Note the number of turns of inductance in circuit.

By Slaby's Wave Meter.—Hold the end of the spiral at which the fluorescent paper is placed to the circuit in which oscillations are taking place and move the earthed rod along the spiral until it is opposite the desired wave length. Then vary the inductance in the closed circuit until the brightest glow in the fluorescent paper is produced. At that time the closed circuit has the wave length indicated by the rod.

By Fleming's Wave Meter.—Move the handle that changes both the inductance and capacity until the pointer is opposite the desired wave length. Bring the copper bar which joins one end of the inductance spiral to the inner tube of the condenser parallel to the plane of the inductance coil of the closed circuit. With a clear, bright spark as before, start the oscillations of the closed circuit which act inductively on the circuit of the meter. Vary the inductance of the closed circuit until the vacuum tube glows most brightly, at which time the circuit has wave length indicated by the pointer.

By Pierce's Wave Meter.—Set the pointer moved by the handle of the variable capacity to the desired wave length. Produce the spark in the closed circuit as before and bring the inductance coil of the meter near the inductance of the circuit under test. Place the telephone receiver to the ear and vary the inductance of the closed circuit until the maximum sound is produced in the telephone. When this is the case the two circuits are in tune.

To Tune the Open Sending Circuit.

Disconnect the closed and open circuits in direct-connected sets as before, and arrange a small spark gap in the aerial in series with it and the ground, and to the terminals of this spark gap add a small spark coil, or connect them to the terminals of the induction coil and have just enough energy to give a clear, bright spark.

If the aerial is inductively connected, remove the inductance to first find the natural period of the aerial.

By Donitz's Wave Meter.—Bring its inductance coil parallel to the aerial. For this purpose a special coil of one turn is furnished for insertion inside the wave meter inductance, and connect this in series with the aerial. As the capacity of aerials is comparatively small, this is done to bring the inductance coil of the meter very close to the aerial. Now vary the capacity of the meter until the maximum reading is obtained, when the natural frequency of the aerial will be indicated by the pointer.

At the same time, it is well to insert the hot wire ammeter in the aerial and note and record its reading for the natural period of vibration.

By Slaby's Meter.—With everything as before, approach the fluorescent end of the helix and move the rod along it until the maximum glow appears. The reading then opposite the movable rod is the wave length due to the natural period of the aerial.

By Fleming's Meter.—With the previous arrangement bring the upper bar parallel to the lower part of the aerial and about 3 or 4 inches from it. The terminal of the vacuum tube which is connected to the outside of the sliding condenser should be connected to earth. Move the handle along the inductance coil until the maximum glow appears in the vacuum tube when the reading opposite the pointer will be the natural period of the aerial.

By Pierce's Wave Meter.—Approach the inductance coil of the meter to the oscillating aerial and close to it, and with the telephone receiver to the ear, move the handle of the condenser. When the maximum sound is heard, the pointer indicates the natural period of the aerial.

After the natural period of the aerial has been obtained by any of the above means, the wave length can be brought to tune with the closed circuit by setting the indicators to the proper wave length in the different forms of meters, and adding a sufficient number of turns of the common inductance in direct-connected sets or of the aerial inductance in inductively-connected sets to give the same frequency as the wave meters, being indicated by the maximum readings of the meters, according to their construction.

Wave Forms.

By the use of Donitz's Wave Meter it is possible not only to obtain the maximum reading of the thermometer, at which time the wave length is indicated, but other readings may be obtained with other positions of the index of the variable capacity, and in this way a series of points may be obtained through which curves may be drawn giving the wave form.

For these curves, wave lengths or indications of the capacity index, are used as abscissæ and thermometer or hot wire ammeter readings, as ordinates according to some convenient scale, and curves are drawn through the points so plotted. They can be plotted for the natural length of aerial; for the aerial with its inductance; and for the natural closed circuit.

A study of these curves will in a general way indicate the sharpness of their resonance and the distribution of energy.

Coupled Circuits.

After the closed and open circuits have each been tuned separately, they are then coupled together. If the wave length is tested after the circuits are coupled, it will be found in general that there are two points of maximum intensity indicated by the wave meters, indicating two wave lengths, though as a matter of fact, the wave curve shows one wave with two humps. If the curve is plotted with wave lengths as abscissæ, and either thermometer or hot-wire ammeter readings as ordinates, one hump will be found to have a greater and the other a less value than the wave length to which one of them separately was tuned.

The **percentage of coupling** is the ratio of the difference between the two maxima to the natural wave length of each circuit, and if closed coupling is desired, the mutual induction between the two circuits is then varied until the two maxima are at the desired points. If very loose coupling is desired, the mutual induction is varied until but one maximum is indicated by the wave meter and this will be very near the natural wave length of each circuit when not coupled.

To Tune the Receiving Circuit.

Receiving circuits should have strong natural periods of vibration, and this can be obtained by large inductances, leaving the tuning to be accomplished by variable capacities. Adding large inductances to the aerial for receiving to increase the natural period, does not have the bad effect of adding it for sending, as it will receive waves of almost any length, but will radiate only feebly if its period is far removed from its natural period. If the receiving circuit has high resistance, the open circuit should be adjusted to the wave length of the sender. However, adding inductance to the closed receiving circuit beyond a certain value, is of no value, as no increase of the natural period will serve to strengthen the signals.

As close coupled senders radiate two waves, one longer and one shorter than the natural period of each, it is possible to adjust the receiving circuit in tune with either wave, but experiment shows that best results are obtained when both the open and closed receiving circuits have the same natural period as the sending circuits and have the same coupling. The longer wave has the lower frequency and has the least damping and consequently greater amplitude or intensity, and if the receiving circuit is to be tuned with only one wave, it would be more advantageous to syntonize with the longer one and disregard the other.

Tuning by Wave Meters.—Of the various forms of wave meters described, only two, the Donitz and Pierce can be used for tuning receiving circuits.

The Pierce Wave Meter is supplied with a special spark gap. The telephonic receiver is removed and the spark gap supplied is put in its place. This attachment has a coil in its base of the proper inductance to replace the telephone. The spark gap should be actuated by a small spark coil by attaching the secondary of the spark coil to the two sides of the wave-meter spark gap which should be opened not more than .1 to .2 of an inch.

The index on the capacity is then set to the proper wave length and the meter used as a sender. It should be placed about three meters from the aerial. Conditions of resonance of the meter with the receiving circuit will be indicated by the maximum sound in

the receiver telephone and can be effected by changing the inductance in the receiver tuning coil.

The Donitz Wave Meter may be used in the same manner as a sender, by arranging a spark gap in the circuit and actuating it by a small spark coil.

It is usual to calibrate one of the elements of receiving circuits. They have either fixed inductance with variable capacity, or vice versa. For one given value of one element, the other may be marked in wave lengths according to its varying values. Thus, in the Stone set, which consists of three coils, inductively connected, the second is calibrated. All have fixed inductances and variable capacities. With the fixed inductance, the frequency or wave length is calculated from different capacities, and the resulting wave length is marked on the handle which moves the condenser plates.

In such cases, if the values of the variable elements are known for different positions of the controlling devices, the tuning can be effected without wave meters, as the different circuits will be in tune with each other when the product of the inductance and capacity in each is the same.

Type E. G. W. Wave Meter.

This wave meter is manufactured by the Telefunken Wireless Telegraph Co. from whom the following description was obtained. A general view of it is shown in Fig. 237.

Uses.

The wave meter may be used for the following operations:

1. Tuning and measuring wave lengths of all the circuits of a radio telegraphic installation, *i. e.:*

a. The closed sending circuit.

b. The open sending circuit (aerial).

c. The closed receiving circuit.

d. The open receiving circuit.

2. Testing of transmitter tone.

3. Testing of detectors for sensitiveness.

4. Determination of capacity, self-induction, coupling coefficients, long distance wave lengths, etc.

Description.

The wave meter is a closed oscillating circuit, consisting of a six-step self-induction and a variable capacity. The principle involved is that of electric resonance. For the purpose of indicating

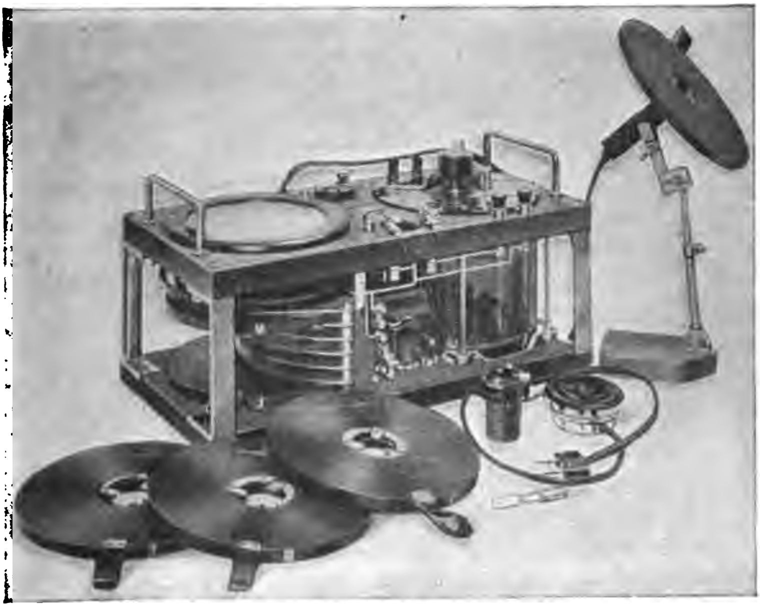


FIG. 237.—General View of E. G. W. Wave Meter.

when the closed circuit is oscillating with maximum energy in resonance with another circuit, a hot wire ammeter, helium tube detector or telephone in series with a detector may be used. When a closed oscillating circuit is acted upon inductively by another circuit, it oscillates with maximum energy when tuned to the circuit furnishing the energy; or, in other words, when two oscillating circuits undergo mutual induction, the receiving circuit takes up the greater part of the energy when they are tuned alike, that is,

when their frequencies of oscillation are equal. Observations for maximum effects on any of the three detectors afford means of bringing the wave meter in resonance with any circuit by means of the variable capacity and six-step inductance. Two scales are provided on the variable capacity which are read by means of pointers attached to the spindle of the movable plate of the condenser. From one scale the amount of capacity in circuit can be obtained from the indicated degrees in arc by reference to accompanying blue prints, which show the absolute value of the capacity for each degree of the scale. Curves are also furnished for each of the six inductance coils which show the wave lengths for the capacity corresponding to each degree indicated on this scale. On the other scale three semicircular arcs permit wave lengths in common use, 400 to 3400 meters to be read off directly. These scales are convenient for roughly and quickly finding the wave lengths; for accurate results the curves should be used.

The steps of self-induction are so arranged that, in combination with the variable capacity, accurate measurements of all wave lengths between 100 and 6000 meters can be made.

Fig. 238 shows the elementary connections of the circuits. *L* is the self-induction coil, *C* the variable condenser, *M* that part of the self-induction that is connected to the hot wire ammeter *W*, *S* the buzzer with a primary cell, *H* the helium tube, *T* a telephone in series with a detector *D*, and *B* a revolving switch by means of which either the detectors or buzzer can be connected across the terminals of the condenser.

The **condenser** is a variable plate condenser secured in a receptacle filled with a specially prepared paraffin oil. It has a set of fixed, parallel and equally spaced plates of semicircular form, all of which are connected to one terminal. A second set of plates connected to the other terminal may be moved into the spaces between the plates of the fixed set by means of a hard-rubber handle which serves to protect the operator from accidental shocks. The effective surface and hence the capacity of the oscillating circuit depends upon the angle through which the movable plates are turned. *F* is a spark gap which short circuits the terminals of the condenser when too great voltages are set up across the plates.

The **self-induction** is built up of helically wound coils mounted in flat discs. On changing discs, the three-coil terminals fit into spring clamp contacts, all six discs having like connections. Care

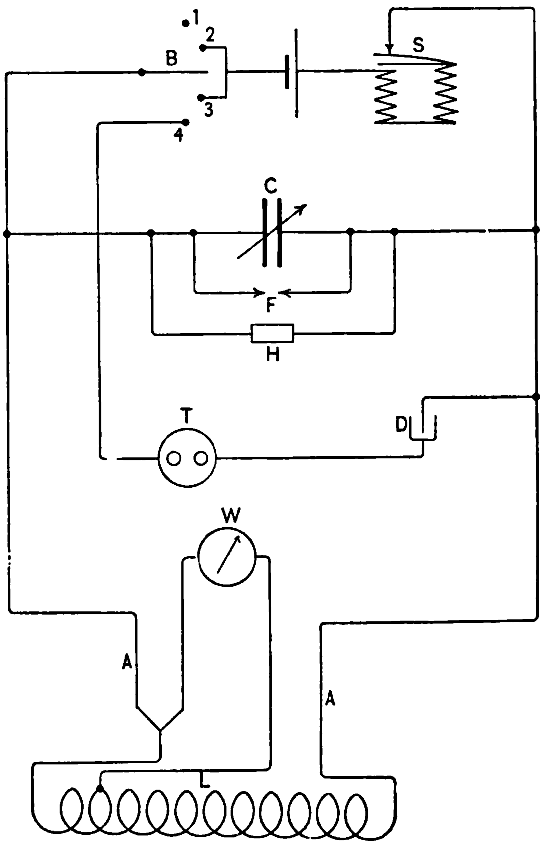


FIG. 238.—Diagram of Connections. Wave Meter, Type E. G. W.

must be taken that the white lines on discs and disc holder correspond when connections are made. The range of wave length for each disc is marked on the back of the disc.

In combination with condenser values from 20° to 170° the in-

ductance coils measure approximately the following wave lengths:

Disc.	Wave length.
I	90- 260 meters
II	180- 500 meters
III	400-1050 meters
IV	650-1800 meters
V	1200-3400 meters
VI	2100-5700 meters

The **hot wire ammeter W** shows the energy load of the wave meter. It is directly connected across a part of the self-induction in such a way that the power taken by the wave meter from the inductance coils is negligibly small, and on the other hand the damping effect in all discs is small and nearly constant. The screw on the side is for adjusting the zero point of the scale. When the hot wire instrument is used, the switch must be on contact 1.

The **helium tube** and **telephone** with detector serve as a substitute for the hot wire instrument when only general results (average of maximum value of energy) are required. The helium tube connects directly across the terminals of the condenser and is clamped under spring contacts which are mounted on the wave meter. When the tube is in use the switch must be on contact 1.

The **telephone T** and **detector** are connected in series across the terminals of the condenser. The telephone can be plugged into the holes *T* and the detector connected at *D*. During their use the switch must be on contact 4.

The **buzzer** and **battery** also connect across the terminals of the condenser, and when they are used, the switch should be on contact 3. Contact 2 is a key contact for making test letters.

As an accessory to the wave meter proper, there is a stand to facilitate changing the connection (relative position of the inductance) with any circuit undergoing test.

Employment

I. Tuning of All Circuits of a Station.

Two circuits are tuned to each other, that is are brought into resonance, when they are of the same wave length or have the same oscillation period. Tuning then is a matter of wave length.

A. Transmission Circuits.

1. Wave Measurement with Hot Wire Ammeter.—This method is specially adapted for the very accurate tuning of wave lengths. Place the movable switch on contact 1. The disc which is connected in circuit with the condenser by means of the flexible circuit *A* is brought close to the oscillation circuit which is to be measured. The pointer of the instrument gives the greatest deflection when resonance is accomplished. The wave length may then be taken from the proper curve, using as an argument the condenser reading in degrees. In beginning do not couple in too fast, lest the hot wire ammeter be burned. (*Note.*—The hot instrument is protected by means of a horse-shoe holding magnet and short circuiting terminals when the needle has been thrown to its limit of deflection.)

2. Wave Measurement with Helium Tube.—The helium tube is clamped under its holding contacts and the switch set on contact 1. The tube is now brought to incandescence by varying the capacity *C*. If the tube remains lighted through a great range of the capacity, the wave meter has been *coupled too closely*. The disc should be removed from the coil undergoing test, until, by means of changes in the condenser, the tube is illuminated within a small range.

3. Wave Measurement with Telephone and Detector.—The detector is connected at *D*, the telephone plugged to *T* with switch on contact 4. The condenser is turned until the maximum sound is received in the telephone. The wave length is then read off from the proper curve. The wave meter should be coupled very loosely with the source of oscillations.

B. Antenna.

The antenna should be placed in direct circuit with the usual spark gap, Fig. 239, or with the buzzer, Fig. 240. Otherwise the measurement is made exactly as described under A.

C. Closed Receiving Circuit.

The wave meter is arranged as a transmitter by setting switch to contacts 2 or 3, and the condenser at the desired wave length for

the disc used. The inductance coil is so arranged that the energy given off by it affects the circuit to be tuned. The capacity or inductance of the closed receiving circuit is then varied until a maximum sound is received. In this case also the meter should be removed from the circuit under test until the detector indicates only within a small range.

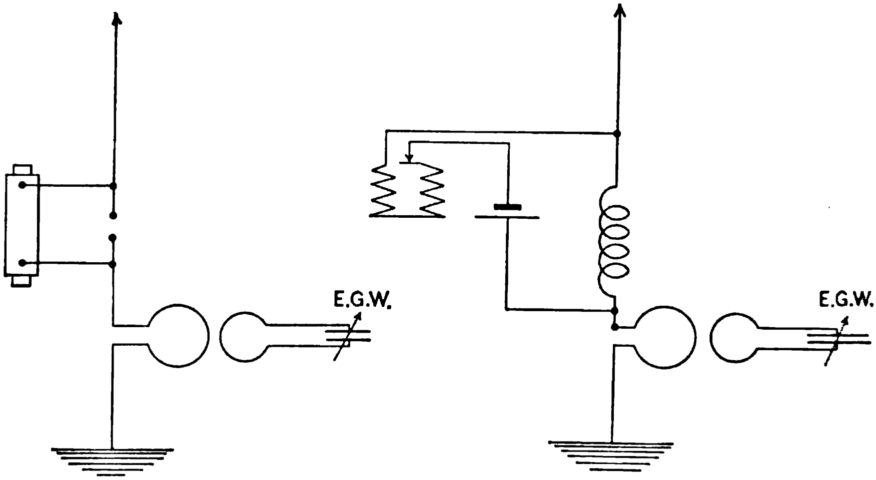


FIG. 239. FIG. 240.

FIG. 239.—Connections for Tuning Antenna Using Spark Gap.
FIG. 240.—Connections for Tuning Antenna Using Buzzer.

D. Receiving Antenna.

The wave meter, set for the desired wave length, is connected as a transmitter, as described under B, and is so placed that it affects the receiving antenna. If the antenna wave is now varied (generally by varying the inductance) the maximum effect on an aperiodic coil coupled with the antenna will give the desired tune.

II. Testing Transmitter Tone.

The wave meter should be loosely coupled with the transmitting circuit, and the detector (preferably *H*) and telephone switched in. The switch should be set on contact 4 and the wave meter brought

to resonance. The tone emitted by the transmitter is then heard in the telephone, and any irregularities of sound due to ragged discharge or the hissing sounds of arcing current can be corrected by changes in the spark gap.

III. Measurement of Sensitiveness of Detectors.

1. Connect detectors in the receiving circuit as usual.
2. Connect wave meter arranged and tuned as a transmitter.
3. The coupling between wave meter inductance and detector should be kept loose until detector approaches limit of receptive ability.
4. Detectors should be exchanged without making any other changes.
5. Tighten or loosen coupling so as to bring the second detector to approximate limit of reception.
6. The looser the limit of coupling, the more sensitive is the corresponding detector, or, the range of the receptive limits will be a measure of the relative sensitiveness of the detectors.

IV. Determination of Electromagnetic Capacity.

1. Arrange a closed oscillating circuit containing a chosen known self-induction L and the unknown capacity C_x.
2. Couple loosely an aperiodic receiving coil with the closed oscillation circuit.
3. Tune the wave meter as transmitter with the closed oscillation circuit.
4. A known capacity C is then substituted for the unknown capacity C_x. C is then varied until the receiving coil is again tuned. The known variable capacity is the equal to the first unknown capacity.

Measurement of Coefficient of Self-Induction.

1. Form a closed oscillating circuit consisting of an unknown self-induction L and a known capacity C.
2. Couple loosely an aperiodic receiving coil with the oscillation circuit.

3. Tune the wave meter to the closed oscillation circuit.

4. Take the value of the wave length from the scale or curve. The self-induction L in henries is then obtained from the formula

$$L = \frac{\lambda^2}{4\pi^2 K V^2},$$

in which λ represents the wave length in centimeters, K the known capacity in farads and V the velocity of light in centimeters.

Measurement of Degree of Coupling of a Transmitter.

If a coupled transmitter is allowed to influence the wave meter, two wave lengths are found, λ_1 and λ_2, as opposed to a wave length λ_c when each circuit oscillates alone. The coupling coefficient is found from the formula

$$K = \frac{\lambda_1 - \lambda_2}{\lambda_c}.$$

Measurement of Wave Length of Incoming Waves.

1. Tune the receiving antenna to the unknown wave.

2. Arrange the wave meter as a transmitter and couple with antenna.

3. Vary tuning of wave meter and loosen coupling until the detector responds only to a certain wave length.

4. The incoming wave length is then equal to the wave length shown on the wave meter.

Note.—The above examples show the many uses to which the wave meter can be put. It follows naturally that there are many other uses which will be understood without further explanation, such as measurement of capacity of antenna, etc.

CHAPTER XXVI.

PRINCIPLES OF WIRELESS TELEPHONY.

Wireless telephony differs from wireless telegraphy in that it transmits articulate sounds while telegraphy limits itself to the transmission of inarticulate sounds, which are made the basis of a code by which words may be sent or received in the form of messages. In telegraphy the sound produced in the telephonic receiver is that due to a certain number of vibrations which fall within the range necessary for the production of sound and the frequency or period of the vibrations is not important; but for the reproduction of articulate sounds, there must be a very wide range of frequencies to correspond to the immense number of vibrations of which speech is composed.

The range of frequencies for the production of sound vary between 16 double vibrations per second and 40,000 double vibrations, the former giving the lowest audible sound and the latter the highest musical note. For the average man's voice, the number of double vibrations per second is 128, and for the average woman's voice, the number is from 256 to 512.

The efforts of the earlier experimenters in wireless telephony were directed to the idea of using the connection afforded by the earth. In general, the scheme consisted in stretching two parallel wires, one at each station, the extremities being taken to earth. In one of these wires was inserted a microphone with a battery of dry cells, and in the other a telephone which reproduced words pronounced at the microphone.

Although such schemes did not require a connecting wire between stations, yet the total length of the parallel wires at the two stations was required to be about the same length as the distance between the stations. Such a telephonic circuit has been in operation for some years in England, where communication is held between the lighthouse on the Isle of Skerry and the coast-guard station of Cemlin, a distance of about three miles.

Theoretical Principles.

In 1878, two American physicists, Graham Bell and Sumner-Tainter discovered that a beam of light that had been made intermittent, falling upon a thin sheet held against the ear, gave a sound, the number of whose vibrations is equal to the number of interruptions in the source of light. By making the duration of the intermissions longer or shorter, the duration of the sound produced was longer or shorter. Any source of light whose intensity can be varied can be used in this experiment but the distance to which the phenomena can be manifested is increased by using a receiving circuit composed of a selenium resistance in series with a telephone and battery.

Crystalline selenium has the remarkable property of being a much better conductor of electric currents when illuminated by a beam of light, and of increasing its conductivity with the intensity of the light. If such a resistance is exposed to a luminous radiation of variable intensity, the variations of intensity will cause variations in the resistance of the selenium and consequently in the battery circuit which will vary the current flowing through the telephone and which will in turn emit sounds corresponding to the changes in the quantity of light.

If the electric arc is used as the source of light, variations in intensity may be produced by certain properties it possesses when arranged as discovered by Duddel, and known as Duddel's singing arc.

Duddel's Singing Arc.—If an alternating current of small intensity be placed in a favorable condition in respect to a continuous current which is feeding an electric arc, the arc itself will emit a sound. At the same time equal oscillations are produced in the light of the arc. If the alternating current is set up in the circuit of a microphone by speaking in it, the oscillations produced in the arc can be received by a selenium receiver placed at a distance, and the luminous oscillations will cause the spoken words to be reproduced in the telephone in the receiving circuit.

The alternating current may act on the circuit which feeds the lamp in a shunt circuit from the feeding circuit, or it may be in another circuit which acts inductively on the feeding circuit.

Fig. 241 shows the connections for the first condition.

R is a resistance wound on a soft-iron core, around which passes the whole of the current feeding the arc. From the ends of the coil is connected a microphone *M*. *R* can be so adjusted that a battery in connection with *M* will be unnecessary. As the microphone is spoken into, the variations in resistance caused by the sound waves changes the current feeding the arc and the light of the arc will vibrate in rhythm with the diaphragm of the microphone and similar vibrations will be set up in the selenium receiver and the words will be reproduced in the telephone of the receiving circuit.

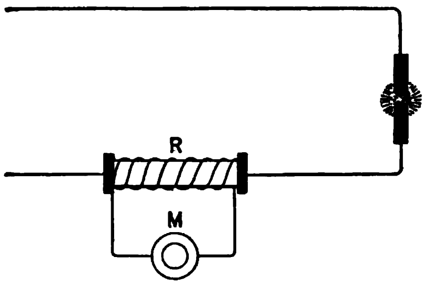


FIG. 241.—Duddel's Singing Arc.

Explanation of the Singing Arc.—In the phenomenon of the singing arc, the variation of the feeding current caused by the superposition of the current due to the microphone develops greater heat in the arc, as the heat is proportional to the square of the current. Similar variations in the volume of the incandescent gases forming the arc are caused by this variation in heat, and these variations in volume are those which generate sound vibrations in the air, reproducing the vibrations in the microphone, and causing the arc itself to sing.

Duddel's Circuit.—In this circuit, the extremities of the arc are joined with a circuit comprising a capacity and inductance as shown in Fig. 242.

D is a generator supplying continuous current to the arc *L*, joined to the extremities of which is a circuit composed of a capacity *C* and inductance *I″*. Such a circuit has a natural period of electrical vibration depending on the values of the capacity and inductance.

If certain conditions are satisfied at the instant when the circuit of the arc is made, the condenser becomes charged and discharged with a frequency depending on the oscillation period of the circuit, thereby producing alternating currents which overlap the continuous current feeding the arc and cause it to vibrate with a period equal to that of the alternating current and the rest of the circuit. If this frequency lies within the range of perceptible sounds, the arc admits a musical note.

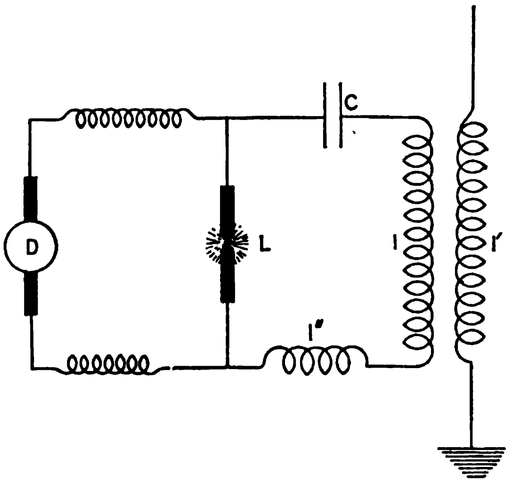


FIG. 242.—Duddel's Circuit.

If the arc is made between the poles of a powerful magnet, either permanent or an electromagnet, both the frequencies and intensities of the alternations are much increased.

This oscillating circuit does not radiate its energy, and to produce radiation, the circuit may be inductively connected through an air transformer to an open circuit which may be made an **aerial** similar to that of wireless telegraphy, one end being grounded. This transformer is shown at I, I', where I is the primary of the transformer inductively connected to the secondary I' which forms part of the aerial, the lower end of which is grounded.

The portion of the circuit $LCII''$ is known as **Duddel's circuit.** This circuit has very little damping, and almost perfect resonance

may be obtained in two circuits, which is very powerful in case of coincidence of frequency of vibration, but which falls off rapidly when the resonance is less perfect.

In such an arrangement as shown in Fig. 242 under certain conditions there would be a continuous radiation from the aerial of a definite period and amplitude. If the amplitude of these waves could be varied by the vibrations due to the voice, the train of radiated waves would consist of all the elements necessary to the transmission of speech.

Such a condition is effected by introducing a microphone in the aerial between the secondary and the ground. If this is now spoken into, the constant radiated energy of the aerial will have superimposed on it the varying energy caused by the changes in the microphone resistance and consequently the radiated waves will have all the varying amplitudes caused by the sounds of the voice speaking against the diaphragm of the microphone.

Electromagnetic Waves.

From the preceding explanation it will be seen that the waves radiated from the aerial of a wireless-telephone sender differ from those of a wireless-telegraph sender in that the amplitude of each wave in a wave train from the former varies according to the impulses that have been given to it by the voice and consist of all the various irregularities of amplitude that are characteristic of sound waves, while those from the latter are probably of nearly equal amplitudes. Aside from this difference the two series of waves are practically the same, with the same characteristic vibrations of the ether at right angles to each other, and are propagated through space in the same manner, guided by the earth through which the lines of force are completed.

Receivers.

The receiver necessary to reproduce every fluctuation of the energy of the transmitter may be any of the various forms of automatically restoring responders using a telephone receiver, such as the imperfect contact coherer, magnetic detector, electrolytic detector, the carborundum or silicon detector. The one said to be the

most sensitive and to give the clearest quality to the reproduced tones is the "Audion," or hot-gas responder, devised and patented by Doctor De Forest, and which can also be used in wireless telegraphy.

Audion.—The Audion consists of a device for detecting feeble electrical currents or oscillations, particularly such as are developed in wireless telegraph or telephone systems. The Audion itself comprises a receptacle, which may be partly exhausted, including a sensitive, gaseous conducting medium, and in which are two electrodes of suitable conductors.

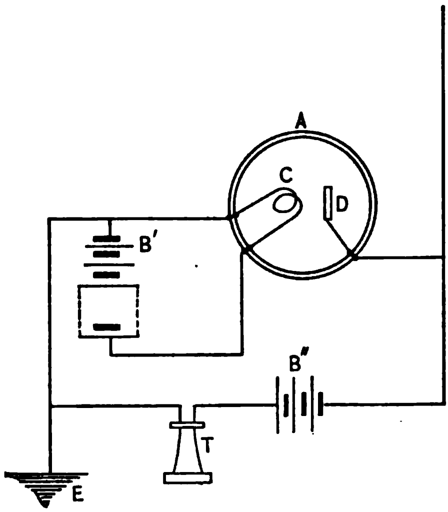


FIG. 243.—Connections of Audion.

The elementary connections of the Audion to the wave intercepter and the signal-producing device are shown in Fig. 243.

In the figure *I* represents the wave intercepter, or the aerial of the telegraph or telephone installation, connected with the earth at *E*. *A* is the Audion with its two electrodes *C* and *D* inclosed within it and which contains air partly exhausted, or a gas containing compounds of the halogens or halogen salts, or mercury vapor. *C* is an ordinary incandescent lamp filament and is connected to a bat-

tery B'. The electrode D may be any suitable conductor, as a plate or disc of platinum.

The gaseous medium inclosed between C and D is rendered sensitive to electrical oscillations by the radiation of heat from the electrode C which is heated by the battery B'.

The passage of electrical oscillations across the gap between the electrodes alters the conductivity of the gas in the gap, and connected in series with this gap is a circuit containing a telephone T and battery B''. When the electric oscillations pass across the gap, the change in the conductivity of the gas produces current variation in the circuit containing the battery B'', causing the telephone, T, to respond. The telephone may be connected either in series or in shunt with the electrodes. The aerial may be connected to either electrode, in which case the other must be connected to earth.

The voltage to be impressed on the electrodes C and D by the battery B'' depends on the nature of the gas between the electrodes and upon the degree of exhaustion within the receptacle, a voltage from twenty-five to one hundred and ten volts is sufficient, the needed voltage decreasing with the degree of exhaustion.

This device is free from all the adjustments required of those detectors that depend for their operation upon variation of resistance of an imperfect electrical contact or counter E. M. F. of a polarization cell.

De Forest Wireless Telephone.

This system designed by Dr. De Forest and made by the Radio Telephone Company of New York has been installed on many of our ships of war. The system is based upon the modulation by a telephone transmitter of trains of electromagnetic waves of relatively high frequencies. These waves are generated in a way, following the methods shown by Thomson and Duddel, such that the frequency of the oscillations becomes so great as to enter the range of Hertzian waves, at which frequencies, energy begins to be radiated into space from the aerial wires.

The direct-current arc is used in connection with an alcohol flame, special arrangements being made to render the arc quiet and free from hissing or popping sounds which would render the

reception of speed more or less obscure. To adapt an arrangement of the low-potential arc to wireless transmission of speech it is necessary to secure a spark frequency exceeding the tones used in speech, and if this frequency be higher than that, having for example, over 40,000 vibrations per second, the pitch of the aerial vibrations produced by the spark becomes so high as to make them inaudible to the human ear, and the articulation and clearness become perfect.

The 40,000 double vibrations correspond to a wave length of

$$\frac{300,000,000}{40,000} = 7500 \text{ metres.}$$

The variation of the amplitude of the radiated waves is accomplished by placing a microphone transmitter in the earth lead of the aerial between an inductance and the ground; this inductance being inductively coupled with the closed oscillating circuit. The microphone is placed near the ground where the high-frequency currents are maximum and the potentials are the least.

The general elementary diagrams of this system is shown in Fig. 244, and the sending circuit can be studied in connection with the Duddel circuit shown in Fig. 242. The receiving circuit can be readily understood from the description of the Audion previously given.

The diagram of connections is shown in Figs. 245 and 246, and with the help of those of Fig. 244 will be readily understood.

In late installations, the appliances are assembled in a compact form in a transporting case which admits of their use in the chart house or emergency cabin or on the bridge.

Instructions for Tuning and Operating De Forest Radio-Telephone Apparatus.

The following directions are furnished by the makers, the Radio Telephone Company, New York. The lettering refers to Fig. 246:

Transmitter, Type C.

Source of Power.—This should be from 200 to 250 volts direct current. From 2 to 5 amperes give best results. If motor generator is used give to it the care any such machine properly demands.

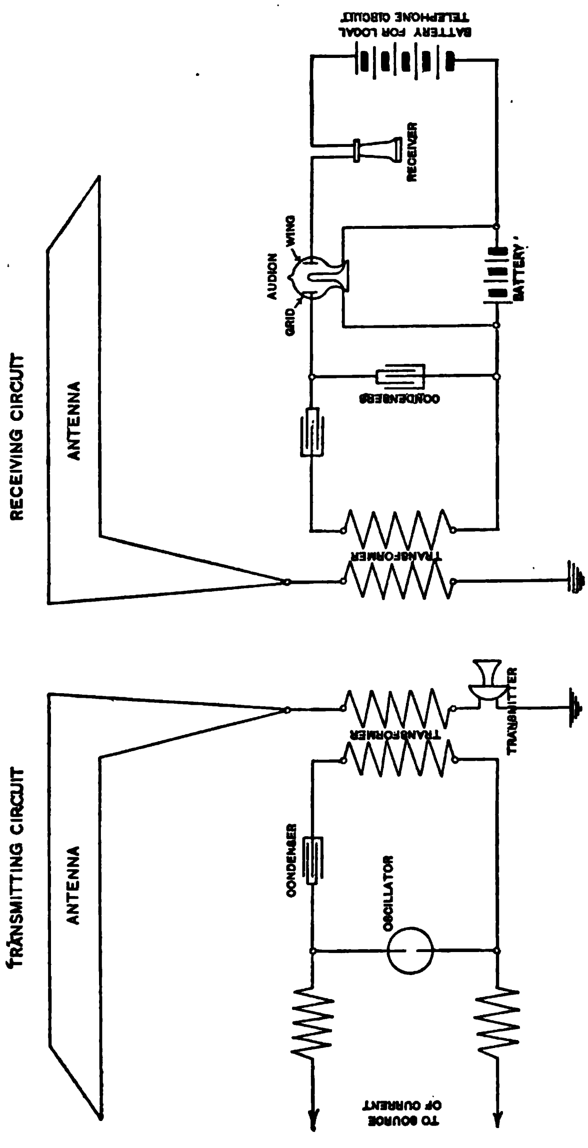


FIG. 244.—Elementary Connections of De Forest Wireless-Telephone Set.

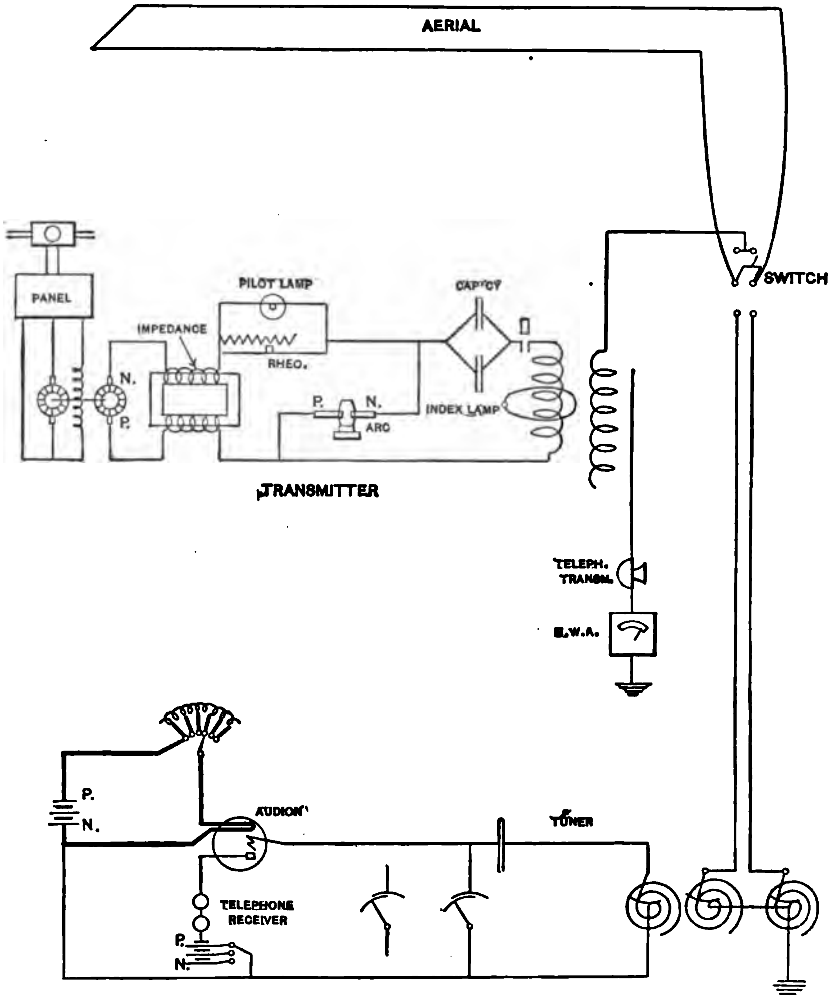


FIG. 245.—Diagram of Connections. De Forest Wireless Telephone Set.

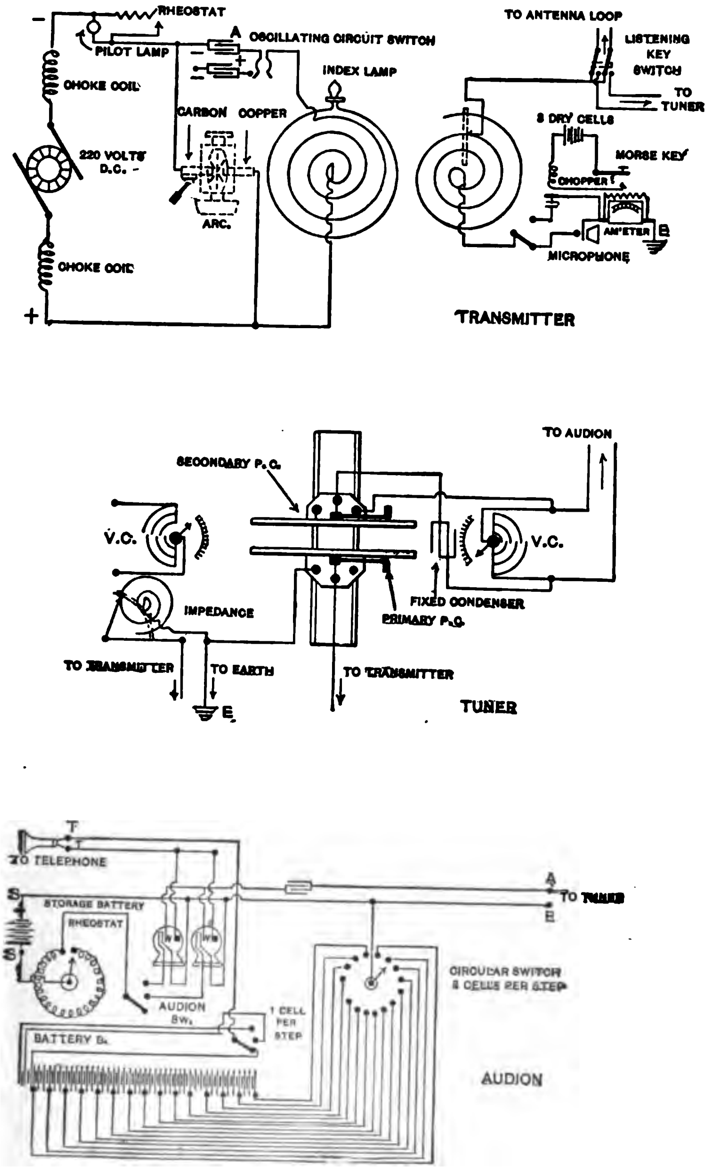


FIG. 246.—Connections of Apparatus. De Forest Wireless Telephone Set.

Rheostat with pilot lamp in shunt thereto must be connected in circuit, preferably between transmitter and choke coil. One choke coil must be in each leg of circuit. Positive lead goes to upper binding post behind lamp (lettered $P+$). This leads to the rear or copper-arc electrode.

Negative lead goes to lower binding post (lettered $P—$). This leads to the lamp bracket and to the front, or carbon, electrode.

Arc Oscillator.—The lamp tank should be kept full of denatured alcohol, and never allowed to get entirely empty. This is important. The tank should be filled full each morning when commencing work.

To facilitate starting oscillator when cold a little alcohol may be poured on wick through top of chimney, but this is not advised.

The opposing faces of the electrodes should be perfectly flat and parallel. After several hours' usage, if arc becomes unsteady withdraw the carbon electrode from the lamp by turning knob counterclockwise until rack clears the gear. If rough file off the face of the carbon with file supplied for this purpose.

Use no other carbons than those supplied with transmitter.

To Start Oscillator.—Close the main line switch. Turn feed knob on lamp until electrodes make contact and pilot lamp lights, then separate electrodes until pilot lamp glows to half-brilliancy Resistance of rheostat should be nearly all in so that arc is just nicely self-sustaining; and once properly set need not be touched thereafter.

The arc is out if pilot lamp is not lit.

The arc is closed if pilot lamp is full brilliancy.

Let arc burn until alcohol lamp is well lit, and arc will begin to oscillate.

Listening Key.—This switch must be depressed for transmitting; elevated for listening.

Glow or Index Lamp.—The little 10-volt lamp directly above transmitter arm will glow as soon as arc begins to "oscillate."

Adjust length of arc until this lamp glows brightly—not necessarily at its brightest.

Tuning the Transmitter.

Condenser.—Open transmitter door and cut in sections A, or B, or A and B of condenser, according to length of wave desired.

Section A contains 3 plates.

Section B contains 4 plates; A and B 7 plates.

Both condenser plugs must be on corresponding pegs of the jack, i. e. both on A (right and left sides respectively), or both on B, or both on AB.

Primary Spiral.—The flexible lead and clip can be attached to any bared convolution of this spiral as desired. The outer turn of spiral is recommended as giving longest wave lengths and steadiest operation of the arc.

Secondary Spiral.—With listening key depressed and index lamp burning, now move the slide knob on front of transmitter slowly up and down until hot-wire antenna gives maximum deflection. The secondary, or antenna, circuit is then in tune with primary circuit.

Fine adjustment of tuning is obtained by moving primary spiral towards or from secondary spiral, but loose coupling is recommended.

The arc should not be opened too wide, or ammeter needle will fluctuate rapidly, indicating that arc is unstable and liable to go out.

Talking.—The small switch on transmitter arm is thrown to its upper position for talking. Hold mouth close in front of mouthpiece and talk directly therein. Speak clearly and distinctly, not too rapidly. Talk loudly but do not shout.

Do not thrust the lips into the mouthpiece, as this renders the words muffled and indistinct.

The megaphone will increase the action on the transmitter. Invert it and speak directly into the larger end.

Listening in.—Keep the head phones on the head, and at end of every sentence throw up listening key with fingers or thumb of right hand, to assure yourself that the other party hears you clearly and answers you.

Never attempt to talk unless key is down and glow lamp lit.

With a little practice two speakers will almost unconsciously depress this key when talking and raise same when expecting a reply,

so that two-way conversations can be carried on almost as rapidly as over the wire telephone.

Microphone.—The buttons become warm but not injuriously so.

It is well to occasionally tap upon the case of the microphones with screw-driver to shake up the carbon granules.

If your own transmission is good you should hear this tapping in your own head receiver very clearly. If you cannot hear this (your receiver of course being in proper adjustment) try adjusting the arc, etc., until you do. The larger the ammeter reading (if steady) the better the transmission.

A frying or scratching sound in the adjacent receiver accompanies the properly oscillating arc.

Receiving Apparatus.

Audion Receiver Lighting Voltage.—The Audion filaments are made for 3 volts—2-cell storage battery only. Higher voltages must not be used, otherwise the filament will soon burn out.

Rheostat should be all in when first connecting up a newly-charged storage battery, i. e. have rheostat index arm turned as far in a counter-clockwise direction as possible.

Audion filament should be bright, but not excessively incandescent.

Battery "B."—The telephone battery is inside Audion case. The switch arms for same are on right-hand side of case.

The circular switch cuts in three cells per point.

Lower switch cuts in one cell per point.

Switch arm must not cover two points at one time, as this short circuits the cells.

Adjust voltage until you hear the signals (from some distant station) at their maximum intensity.

If this voltage be made too high the blue cathode arc is seen in the bulb, and sensitiveness is diminished.

Once adjusted both rheostat and "Battery B" switches should remain set. These should not be thrown back to zero when sending. Breaking the Battery A (lighting) circuit also interrupts the telephone circuit, and it is sufficient merely to break this *A* circuit when sending with a powerful spark, in order to prevent the

Audion's responsiveness from being even momentarily interrupted by said spark.

Always cut off storage battery by means of switch on left side of receiver box when Audion is not in use. Do not forget this.

As the storage battery runs down cut rheostat resistance out gradually. Keep a duplicate battery always charged in readiness.

If voltmeter be connected across storage battery see that voltage is never too high for the Audion filament.

Double-Filament Audions.

The double filament has twice the life of a single filament. When first filament has burned out unwrap the small bare copper wire which is coiled around the glass neck of the bulb and tuck it under the little brass clip which is soldered on to the outside cap of the stem; or twist this copper wire around the wire stub soldered to this cap. This will put the second filament in the circuit, and Audion is then to be replaced in its receptacle inside the box.

Connect the red wire lead to small binding post marked red; the green lead to binding post marked green.

Tuning the Receiver.

"Pancake" Tuner.—Have the two tuner pancakes approximately ¼ inch apart at the start. Connect the "Impedance" binding posts one to one lead from the transmitter box and the other to the earth lead. These binding posts are lettered *I* and *E* respectively. Connect the other lead from the transmitter to center binding post of primary p. c. (lettered *A*) and the earth lead to one of the other two binding posts on the p. c. (lettered *O* or *I*). Connect Audion binding posts marked *A* and *E* to the two binding posts on end of tuner box marked *VC*. The lead to *C* leads also over to the binding post (lettered *A*) on the secondary p. c. Connect the flexible lead from the fixed condenser inside the tuner box to the binding post on the secondary p. c. (lettered *O* or *I*).

Adjust the two swinging arms and the "Impedance" arm to give maximum sound in telephone receiver from distant transmitting station.

Then adjust capacity of variable condenser (*VC*) in shunt across the two Audion leads, to further increase signals, or cut this *VC* out entirely, according to length of wave to be received, etc.

Finally, or to cut out interferences, separate the p. c's. by a distance giving the loudest signals, thus "loosening the coupling."

The tuning by means of the contact arms now becomes sharper. For undamped oscillations from the radio-telephone transmitter tuning may be made exceedingly sharp.

A little practice and manipulation will enable one to cut out powerful interferences, and to "bring in" the desired station much more loudly than seems possible on first attunement.

For special work the extra variable condenser (*VC*) at the back of tuner box is to be connected in any part of the tuner circuit where it may be needed; for example, in the antenna lead to primary p. c., or in series in the Audion, or secondary, circuit.

The Audion has an excessively small electrostatic capacity, hence tuning with it is extremely sharp.

By adjustment of Battery B on Audion it is possible under some conditions to effect a separate method of tuning auxiliary to the usual method. But once attuned to a given radio-telephone transmitter this tuner and Audion receiver require little attention.

Antenna.—The "Loop" antenna should always be used in receiving. Connect one end thereof to each of the antenna leads coming out from the top of the transmitter case.

Earth Lead.—This lead should be as short as possible from "Earth" to the hot-wire ammeter and thence to lower binding post (marked *E*) on transmitter case. Run a spur lead from earthed side of ammeter to the "Impedance" binding post lettered *E*, and to binding post marked *A* on primary p. c. of tuner.

To Telegraph.

The two extra leads from transmitter arm must be connected to the two rear binding posts on the "Chopper" telegraph box (lettered *M*). Connect three cells of dry battery in series to the two left-hand binding posts (lettered *B*). Now throw the small switch arm on transmitter arm to its lowest contact.

By means of the small screw-driver adjust (when necessary) the

"chopper" contact in bottom of box (reached through the single hole in top of chopper box) until the hot-wire ammeter needle's throw is reduced to about one-half its normal reading when the telegraph key is held closed.

The Morse sending key may be operated at the highest possible speed. This chopper telegraph may be also used for calling purposes.

Remember always to throw the transmitter arm switch *up* for talking.

Care of Apparatus.

It is very important that all parts be kept clean and dry, especially when exposed to salt sea air and moisture. Keep doors of hood closed as much as possible, and all metal parts wiped dry, or with cloth dampened in "3 in 1" oil.

If moisture gets in telephone cords it tends to short circuit same, reducing the received signals.

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